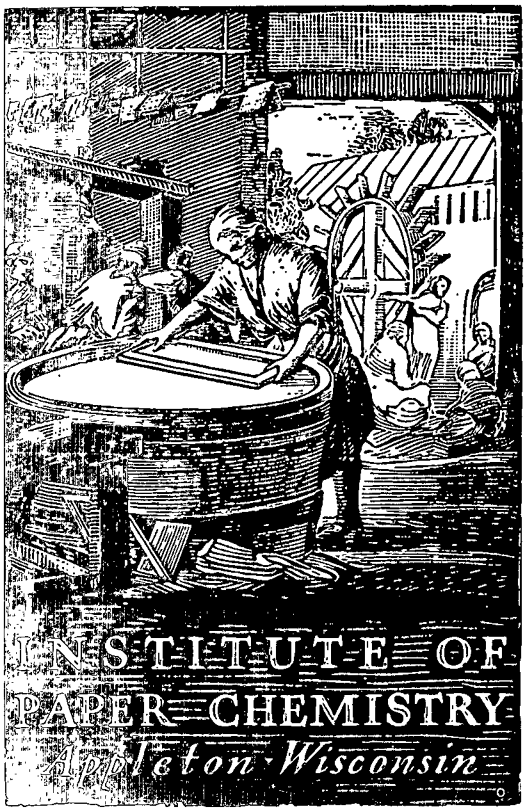
M, LORENZ



OPTIMIZATION OF MACHINE PROPERTIES FOR COMPRESSIVE STRENGTH: SURVEY OF FACTORS AFFECTING COMPRESSIVE STRENGTH

Project 2695-22

Report One
A Progress Report
to
FOURDRINIER KRAFT BOARD GROUP
OF THE
AMERICAN PAPER INSTITUTE

March 15, 1982

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

OPTIMIZATION OF MACHINE PROPERTIES FOR COMPRESSIVE STRENGTH: SURVEY OF FACTORS AFFECTING COMPRESSIVE STRENGTH

Project 2695-22

Report One

A Progress Report

to

THE FOURDRINIER KRAFT BOARD GROUP

OF THE

AMERICAN PAPER INSTITUTE

March 15, 1982

TABLE OF CONTENTS

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

OPTIMIZATION OF MACHINE PROPERTIES FOR COMPRESSIVE STRENGTH: SURVEY OF FACTORS AFFECTING COMPRESSIVE STRENGTH

SUMMARY

The project has been initiated because compressive strength is an important property of linerboard and medium. While much is known about factors influencing compressive strength, better ways to maximize compressive strength in relation to Mullen and other properties are needed. The objectives of this initial survey were to analyze information in the literature on basic factors affecting compressive strength and to identify gaps in existing knowledge and opportunities for new technology.

Based on current evidence on the mechanism of compressive failure, it appears that density (fiber bonding) is a major factor affecting compressive strength. For well-bonded sheets the fiber modulus and strength may limit the ultimate edgewise compressive strength. Because of the importance of density, practical ways to densify the sheet are needed.

The compressive and tensile properties of paperboard are affected differently by papermaking factors. Compressive strength is favored by well-bonded stiff thick fibers, such as those of hardwoods, and appears to be relatively insensitive to pulping yield at constant density. This creates opportunities to reduce costs by utilizing increasing amounts of high-yield hardwoods and recycled fiber. Current technologies could make use of more hardwoods than usually used today. However, optimization of pulping, refining, and pressing is needed to fully realize the fiber potentials. For maximum hardwood utilization in linerboard, new technology is needed, particularly in pressing and drying.

[Note: A definition of terms and compressive strength units is appended to this report. Common conversion factors from English to ISO metric units are shown because of the mixed use of both types in the literature.]

Figure 1 illustrates the general effects of selected papermaking factors on compressive strength. These include density (fiber-to-fiber bonding), fiber orientation, drying strain, fiber properties, pulp yield, and thickness (z) direction fiber orientation (high consistency forming). Both CD and MD compressive strengths are considered. CD compressive strength is the dominant factor affecting top load compression, and MD compressive strength is necessary for flat crush rigidity. In general, board properties in both directions must be considered.

High compressive strengths are favored by increased density, high fiber compressive moduli and z-direction fiber orientation (high consistency forming). Density is a major factor because of its effects on fiber bonding. Figure 1 also shows that increasing fiber orientation and MD drying strain have opposing effects on MD and CD compressive strength. Tensile properties exhibit similar trends, but the magnitudes of the orientation/strain effects are different. In general, it is desirable to optimize orientation/strain effects where process and performance requirements involve MD and CD compressive strength and other properties. Corrugating medium requires a proper blend of MD and CD properties to maximize formability and end-use performance. Linerboard needs high CD compressive strength, but suitable MD properties are also required for some performance aspects.

Compressive strength does not appear to be greatly affected by higher yields if the board is densified to obtain good fiber-to-fiber bonding. This can be an important factor in future linerboard developments.

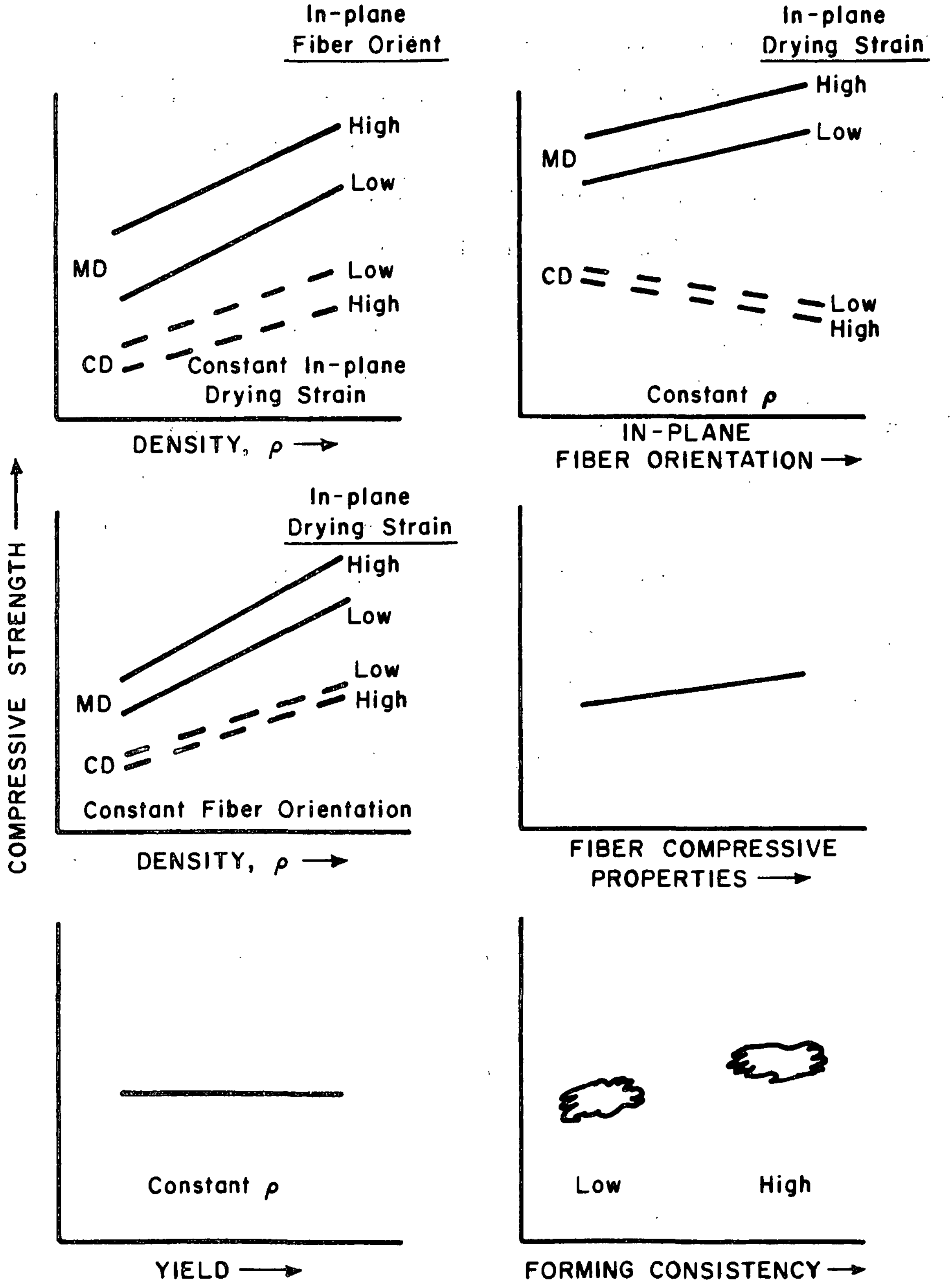


Figure 1. Effects of selected papermaking factors on compressive strength.

Our survey shows there are opportunities to improve cost/compressive performance ratios for linerboard and medium by proper utilization of high-yield hardwood and recycled fiber. Much can be done using current technology, but we need to know how to select the best pulping and papermaking conditions. Our future work will be directed to analyzing the potentials of existing and new technology.

Combined board ECT is primarily dependent on the CD edgewise compressive strength of the components and, hence, density. However buckling of the flute elements can occur in the short column test, particularly with lightweight components. In this case both the compressive and flexural properties of the components are involved, and these are affected differently by density. However, an approximate analysis indicated that increased fiber bonding and density of the components can be expected to increase combined board ECT even when the component elements buckle.

INTRODUCTION

A goal of the corrugated box industry is to make more efficient use of fiber and energy in the manufacture and application of corrugated boxes. To achieve this goal we must maintain and improve the cost/performance ratio of our corrugated products. To this end corrugating components are needed which have the best overall properties for fabrication, conversion and end-use performance. Both linerboard and medium must be considered. The components must run well on the corrugator at high speeds; they must have good runnability and gluability characteristics. The combined board must meet regulatory requirements and perform well in service.

Box compressive strength is the single most important end-use attribute. Many users are placing increased emphasis on box compressive strength in their requirements. We know box compressive strength is primarily dependent on the compressive strengths of the linerboard and medium. As one consequence the FKBG/FBA Ad Hoc Rule 41 Committee is considering proposals to restructure Rule 41/Item 222 specifications. The committee is considering alternatives to Rule 41/Item 222 which will place more emphasis on minimum values of combined board edgewise compressive strength (ECT) and less on combined board Mullen.

Regardless of proposed specification changes, we believe future fiber and energy needs will encourage changes in the characteristics of components. More emphasis will be placed on compressive strength and less on Mullen. This creates papermaking opportunities. Thus, we need to consider better ways to optimize compressive strength in relation to other properties such as Mullen while maintaining or improving the appropriate fabrication and conversion properties.

The proposed rule revisions provide impetus for research on optimizing component properties. However, even in the absence of the proposed changes better ways to optimize cost/performance benefits are needed to conserve fiber and energy.

Therefore, the objectives of this initial survey project were to analyze information in the literature on basic factors affecting compressive strength and to identify gaps in existing knowledge and opportunities for new technologies.

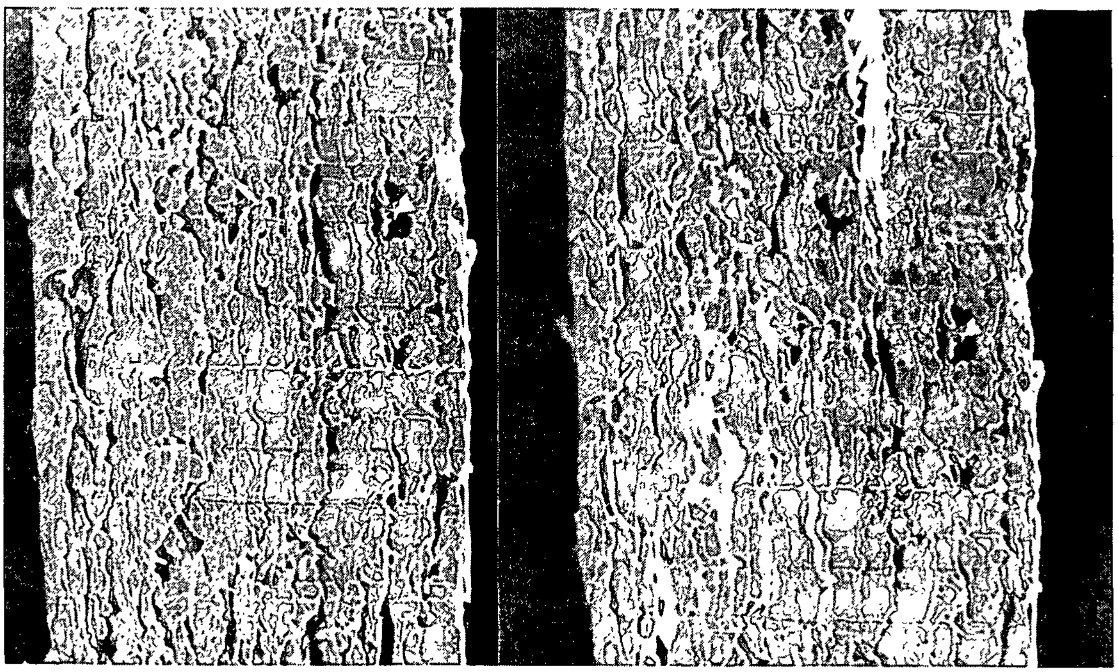
COMPRESSIVE STRENGTH

COMPRESSIVE FAILURE MECHANISMS

The SEM micrographs in Fig. 2 show that the sheet expands and the voids enlarge under compressive load. Fiber bond disruption along planes of weakness occurs as the sheet fails. The planes of voids and weak bonding are believed to reflect the layered structure of paper or board. Sachs and Kuster (1) suggest that failure originates due to a combination of the enlargement of voids, tearing of fiber cell walls and separation between fiber layers. They indicate that parting of the S1/S2 cell walls leads to separation of fiber-to-fiber bonds. Seth (2) and Fellers (3) also concluded that compressive strength may be limited by the compressive strength of the fibers for well-bonded sheets. Thus, based on visual and other evidence, compressive strength is highly dependent on bonding (density) and is believed to be limited by fiber modulus or strength on well-bonded sheets.

Figure 3 shows that the edgewise compressive strength of handsheets formed from earlywood and latewood fibers is strongly dependent on sheet density as are many other properties of paperboard (2, 4-9). We obtained similar relationships for the STFI (short span test) and Weyerhaeuser lateral support tests, although the test magnitudes were different at a given density. Under most papermaking conditions an increase in density is accompanied by an increase in fiber bonding. Thus, edgewise compressive strength and other properties such as burst and tensile strength increase in approximately a linear fashion with density.

In our recent work, fiber modulus (E) measurements were made on pulped but unrefined early and latewood fibers from a number of species (4). Figure 4 shows that at a given density the compressive strengths of sheets made from the pulped fibers increased as fiber modulus increased. In general, compressive strength increased with increasing fiber modulus over a wide density range (Fig. 5). Analysis of the data indicates that the effects of density changes on compressive strength are more than twice as great as changes in fiber moduli. Therefore density is the major factor governing compressive strength, although the fiber characteristics also affect compression. This agrees with the visual observations previously discussed. In addition, Seth et al. (2) showed that the compressive strength of kraft pulp increases up to about 4 km (39 Nm/g) with increasing wet pressure. The compressive strength then levels off. The plateau was relatively constant over the yield range studied, with a slight maximum at 52% yield (see Fig. 6). (Note: Other studies on yield effects are discussed in later pages.) An even more pronounced plateau region was obtained on stock beaten to 500 mL CF. Seth concluded that the compressive strength at moderate degrees of bonding is controlled by the compressive strength of fibers. Thus, the compressive characteristics (strength and/or modulus) of the fiber is one of the factors affecting compressive strength.



UNCOMPRESSED (100X) COMPRESSED (100X)

Figure 2. Sheet expansion and fiber bonding disruption along "planes of weakness" (white regions at right).

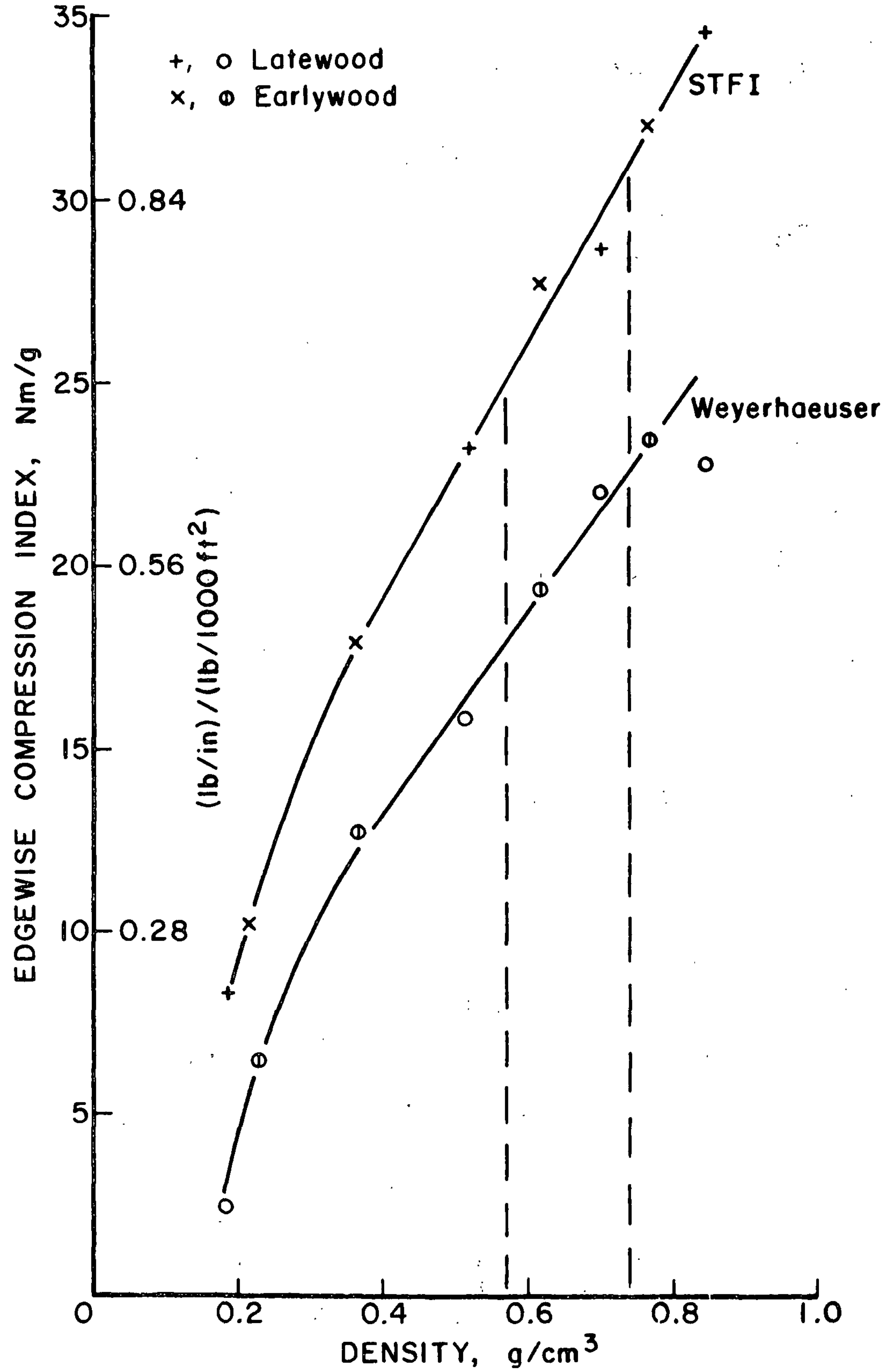


Figure 3. Edgewise compressive strength vs. density (loblolly pine). (Density range for commercial 42-lb kraft liner shown by dashed vertical lines.)

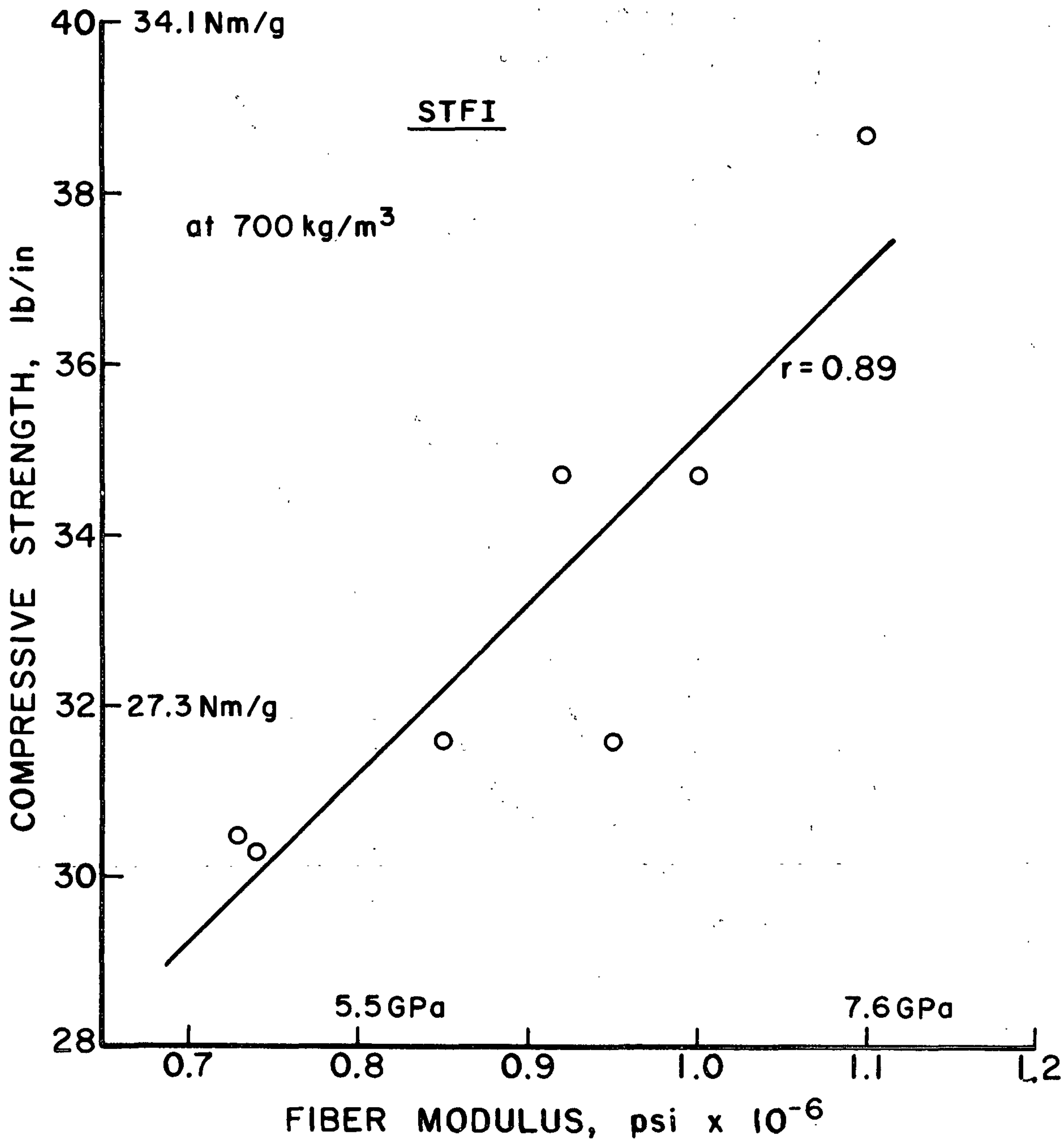


Figure 4. Relation of compressive strength (STFI) to fiber modulus at a density of 700 kg/m^3.

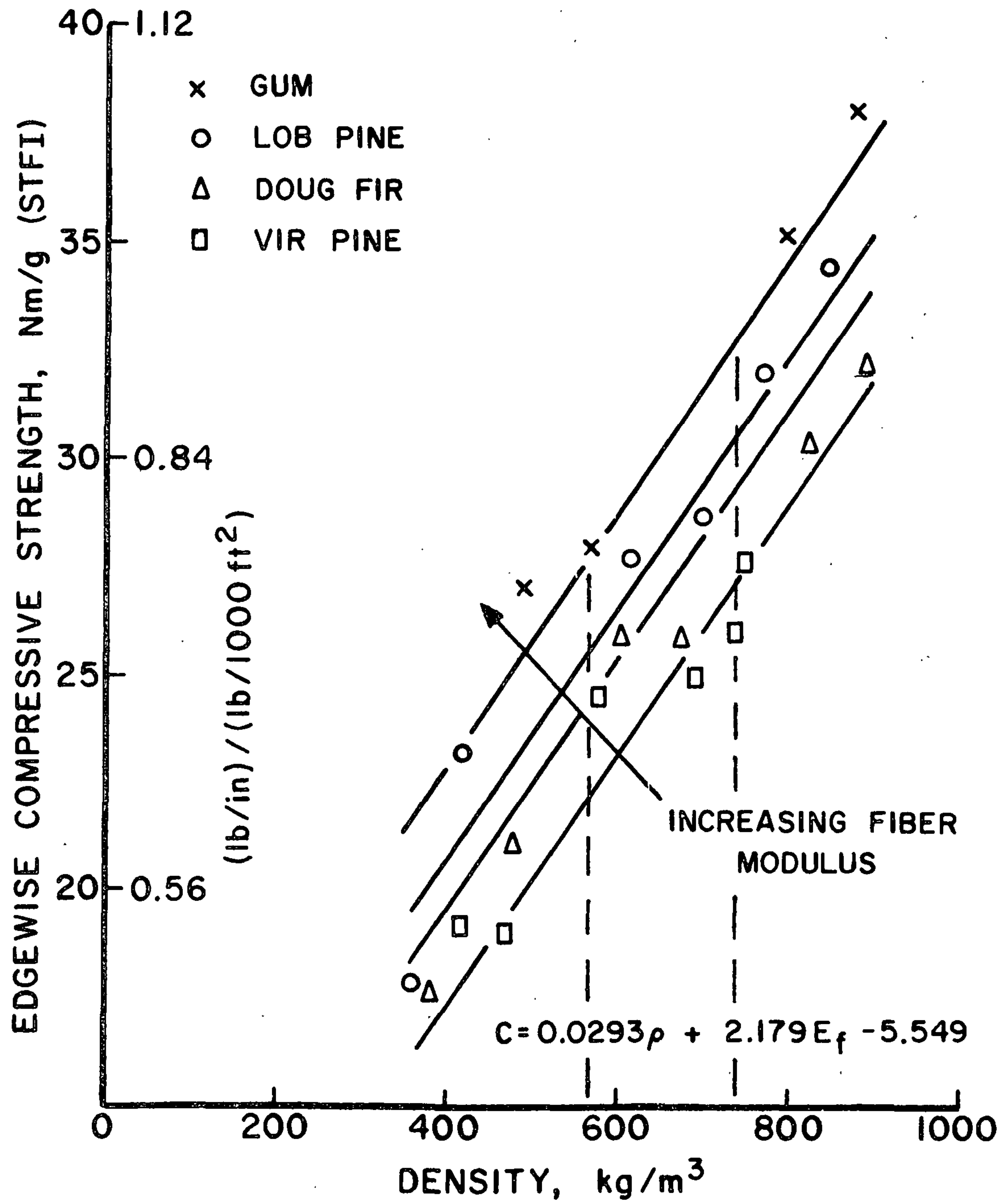


Figure 5. Edgewise compressive strength, STFI, (C) vs. density (ρ) and fiber modulus (E_f). (Density range for commercial 42-lb kraft liner shown by dashed vertical lines.)

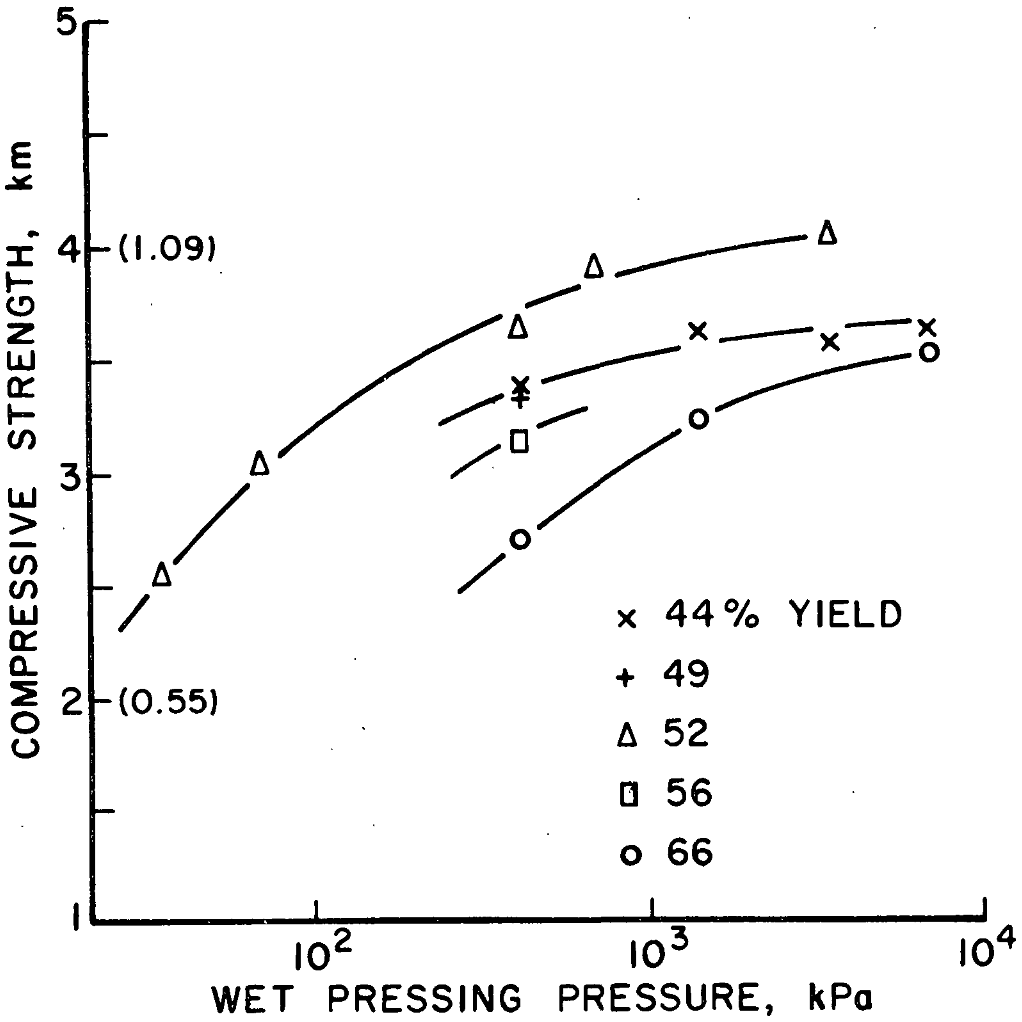


Figure 6. Compressive strength vs. wet pressing pressure for kraft pulp at 650 mL CF (Seth et al., Tappi, 1979). [Vertical scale values in parentheses are in (lb/inch)/(lb/1000 ft^2).]

Figure 7 compares tensile and compressive results on sheets made from early and latewood fibers (4). At practical densities the compressive strength is much lower than tensile strength. This fact has been noted by many investigators (1-4, 10). They have also noted that the strain at failure is much lower in compression than tension (see Fig. 8). Our results also showed, as expected, that the sheets formed from earlywood and latewood fibers gave different tensile strengths. However,

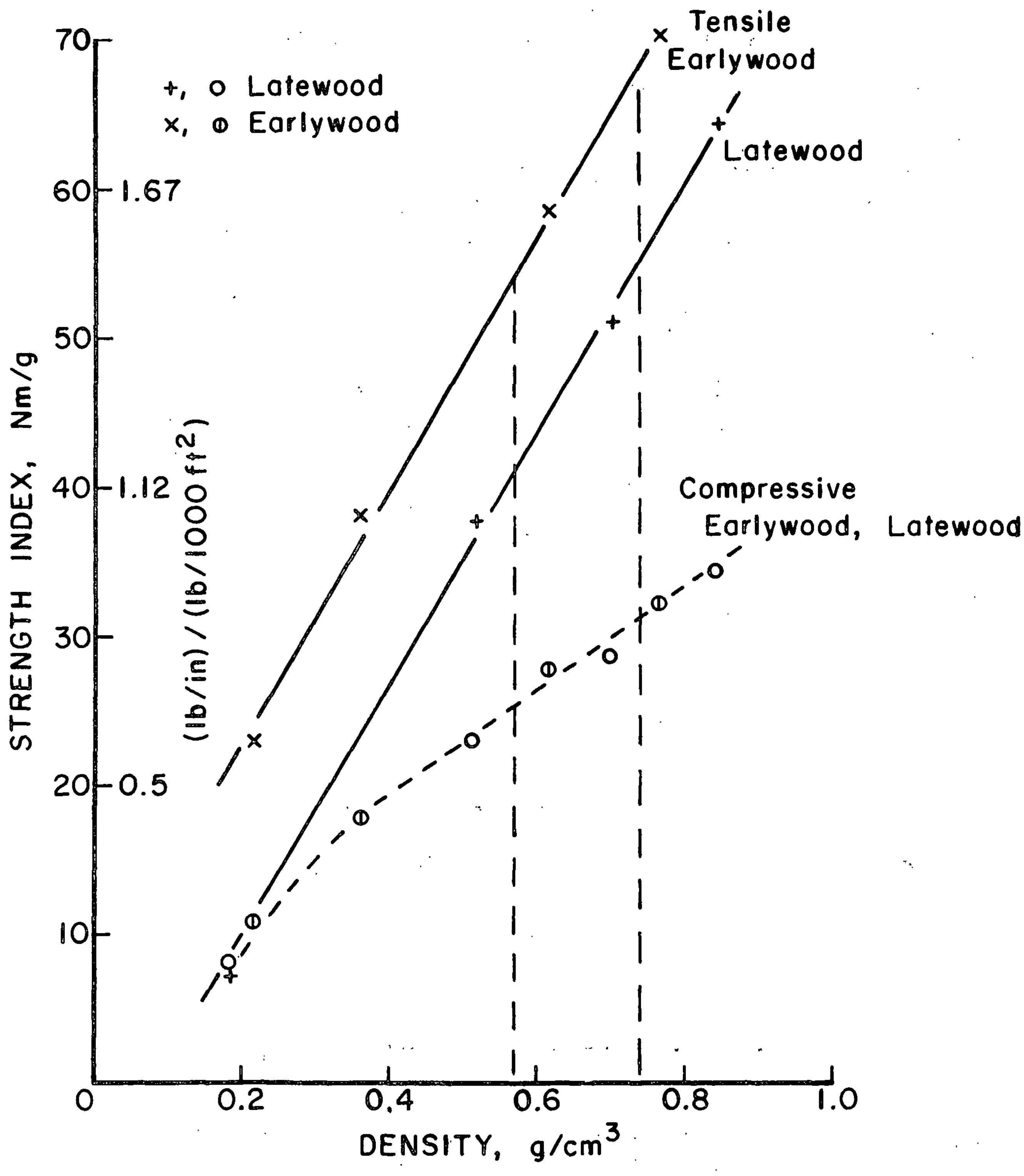


Figure 7. Tensile and compressive strength vs. density (loblolly pine). [Density range for commercial 42-lb kraft liner shown by vertical lines.]

at equal densities the compressive strengths were about the same. The similar compressive behavior of the earlywood and latewood fiber sheets is believed to be due to the fiber moduli being about the same (4).

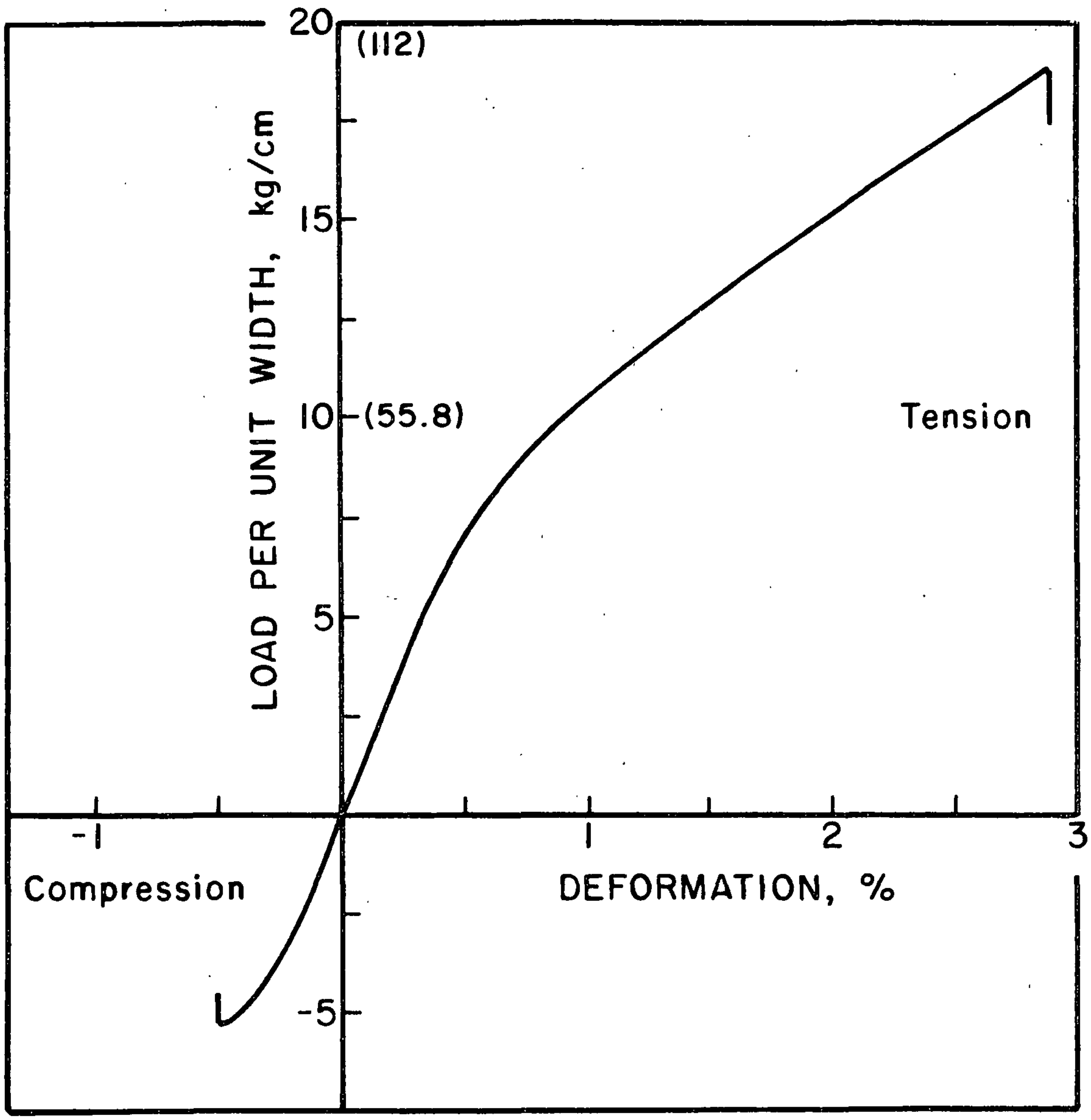


Figure 8. Load-deformation curves in compression and tension [from Seth et al. (2)]. [Values in parentheses on load scale are in lb/inch.]

Fellers (3) showed that compressive strength is relatively constant over a yield range from 48 to 66% at constant density and hemicellulose content (Fig. 9). The compressive/tensile ratios in Fig. 10 show that tensile and compressive strengths were affected differently by yield - i.e., tensile tended to decrease with increasing yield, whereas compressive strength was relatively constant. Fellers et al. (3) suggested that lignin contributes to load-carrying ability in compression but not in tension. Based on the effects of yield, moisture content and stress-relaxation studies, they concluded that the low compressive strength and strain-to-failure compared to tensile properties is due to structural instabilities and yield phenomena. Also, viscoelastic compressive behavior is consistent with instability failure [see Ref. (11)].

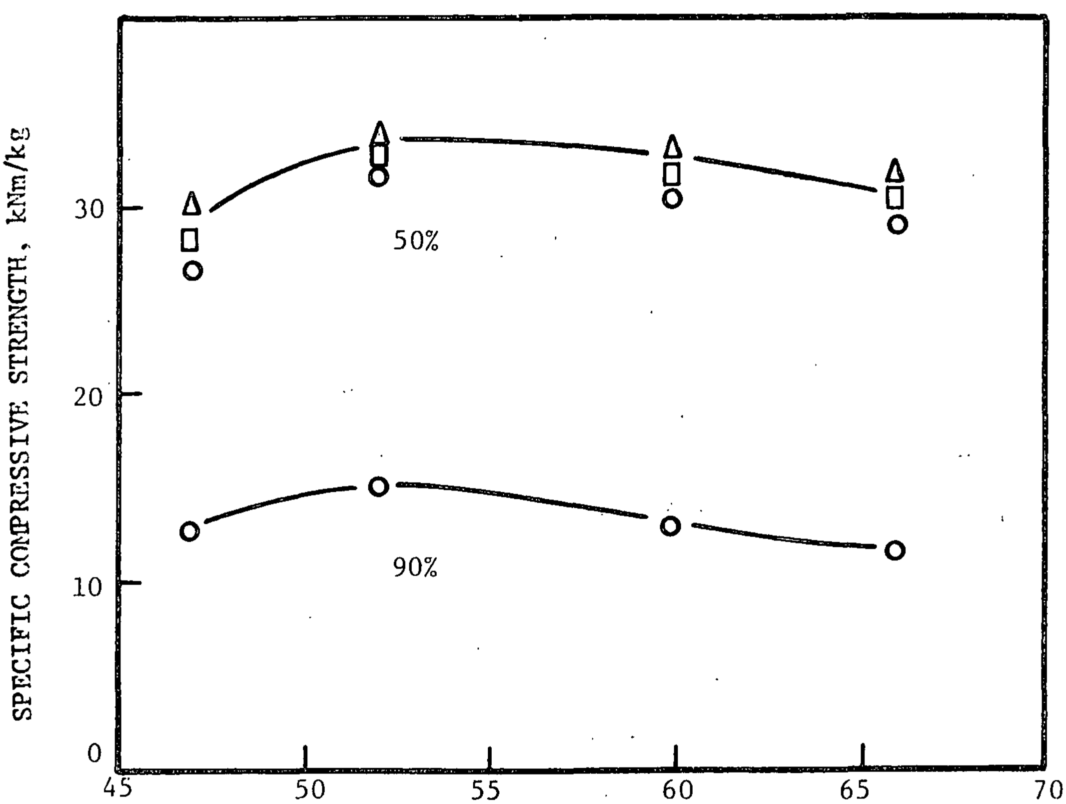


Figure 9. Specific compressive strength vs. yield at two relative humidities (50 and 90%). Key: O = 17°SR; □ = 22°SR; = 30°SR (from Fellers, C. et al.; Tappi, June, 1980).

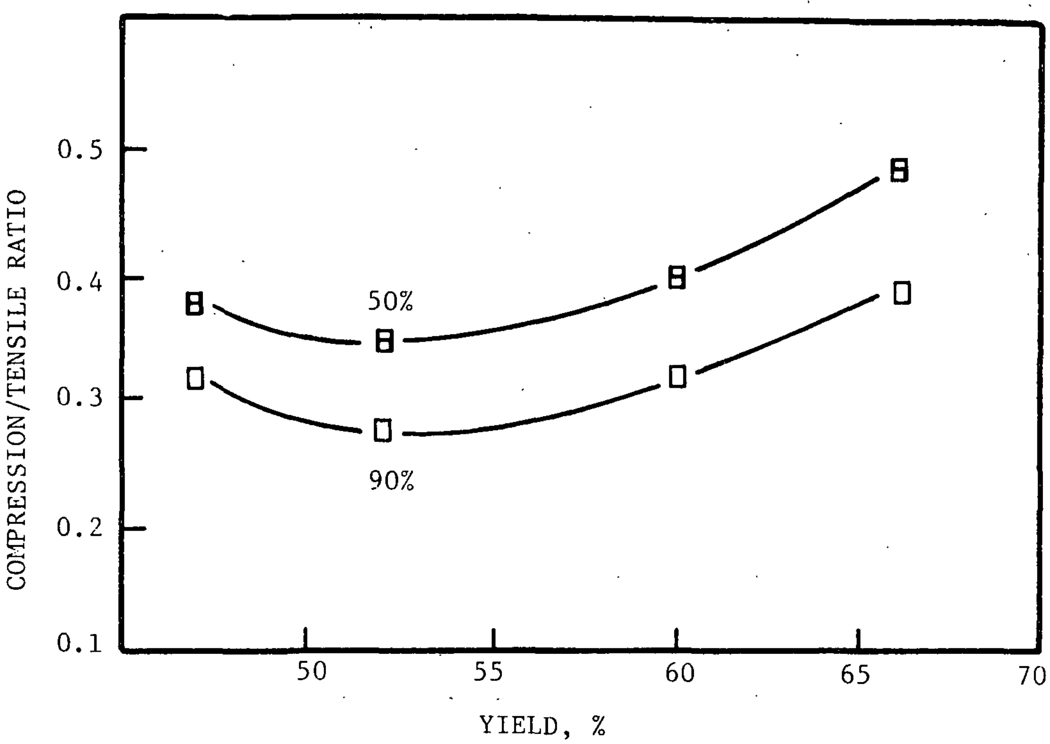


Figure 10. Compressive strength - tensile strength ratio vs. yield at constant density and at two relative humidities (from Fellers, C. et al.; Tappi, June, 1980).

Koning and Haskell (12) also showed that compressive strength is primarily affected by factors influencing density, such as pressing and refining. On the other hand, tensile strength and modulus were affected by wood yield and species as well as pressing and refining (Table I).

Various furnishes differ in their compressive and tensile potentials at a given density. For example, Fig. 11 and 12 taken from work by deRuvo et al. (13) show that NSSC hardwoods and recycled corrugated have relatively low tensile strength compared with unbleached kraft; however, the NSSC and recycled corrugated have relatively good compressive potentials. Our work on recycled old corrugated also shows that the medium fraction has high compressive strength at a given density

(14). We believe this creates papermaking opportunities in the manufacture of linerboard.

TABLE I

SIGNIFICANT PAPERMAKING FACTORS AFFECTING STRENGTH AND MODULUS[a]

Compressive Strength	Tensile Strength	Tensile Modulus	Tearing Strength
1. Wet pressing	1. Wood species	1. Wood species	1. Wood species
2. Freeness	2. Yield	2. Yield	2. Yield
	3. Freeness	3. Freeness	3. Wood X pressing
	4. Wet pressing	4. Wet pressing	
	5. Wood X yield		

[a]From Koning, J., Jr. and Haskell, J. H. Pbd. Pkg.: 32, 34, 36, 38, 40, 42, 44-46, 48, 50(Oct., 1979).

Past work at the Institute has shown that compressive strength increases rapidly with increasing z-direction (transverse) bond strength up to a certain level of bonding (15). Above the critical bonding strength level compressive strength increased more slowly as z-direction bond strength increased. Among other things, high consistency forming has been shown to produce large increases in internal bond strength (16). These are accompanied by increases in compressive strength and losses in tensile strength. The increases in compressive strength and bonding have been attributed to greater thickness direction fiber orientation, another possible avenue for compressive strength improvement.

We speculate that the compressive strength of paperboard is limited by the bending and buckling instability of weakly bonded fiber layers, layers separated by voids, and fiber elements. Figure 1 supports this view, as do the comments of other investigators on the growth of voids in the sheet as load is applied. In this connection Perkins et al. (17) have emphasized the importance of the transverse shear modulus in the elastic and inelastic range to compressive strength based on an internal stability analysis. Institute work in progress shows that compressive strength is well related to the transverse shear and in-plane moduli. Both properties are important in various stability models under study. In principle those properties can be measured on-machine and, hence, facilitate optimization and control of compressive strength and other properties dependent on fiber bonding.

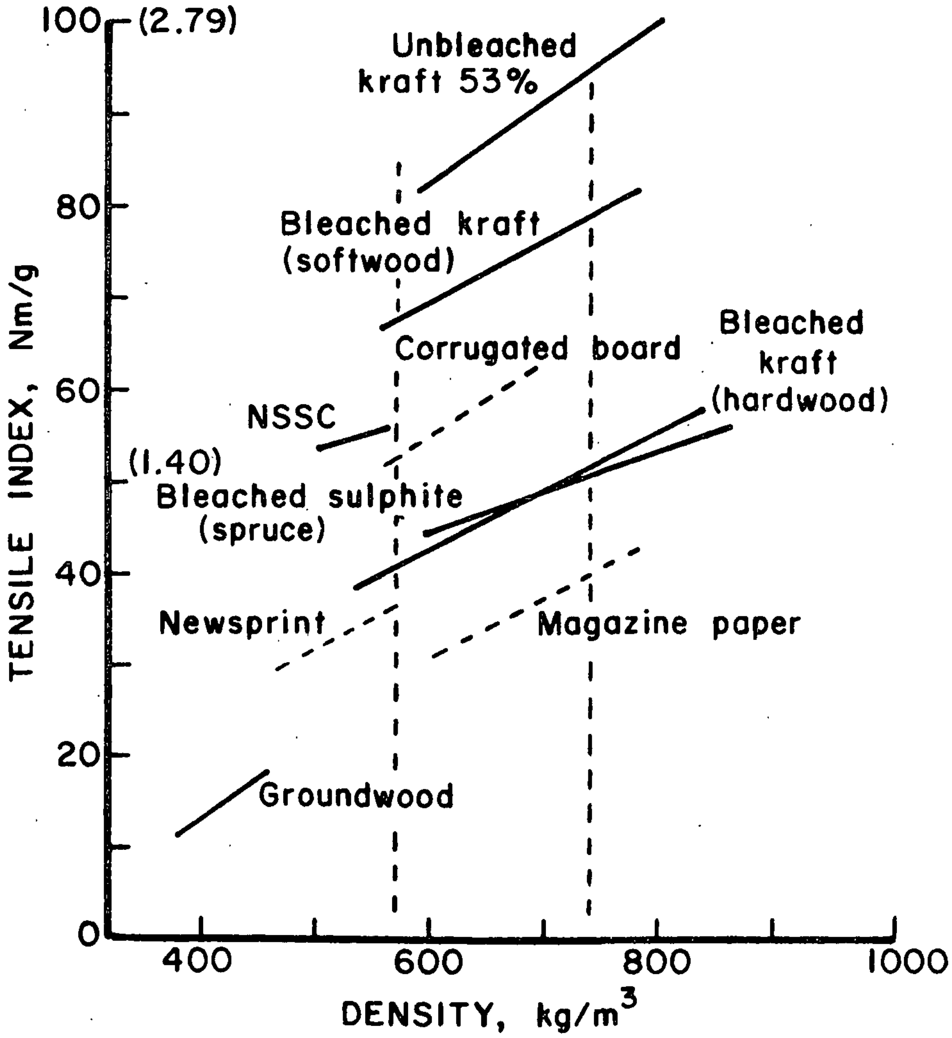


Figure 11. Tensile strengths of various fiber types (from deRuvo et al., Svensk Papperstid. 1978). [Density range for commercial 42-lb liner shown by dashed vertical lines; load scale values in parentheses are in (lb/inch)/(lb/1000 ft^2).]

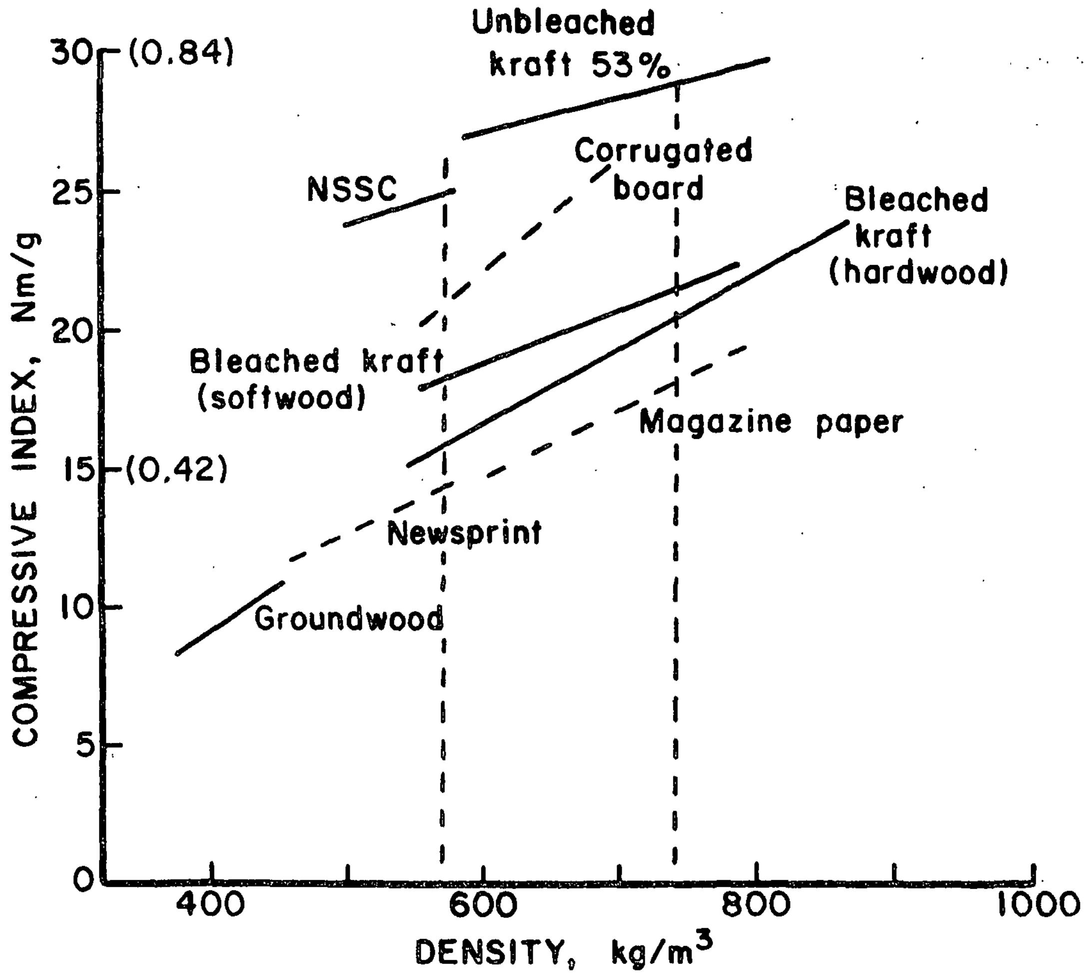


Figure 12. Compressive strengths of various fiber types (from deRuvo et al., Svensk Papperstid. 1978). [Density range for commercial 42-lb liner shown by dashed vertical lines; load scale values in parentheses are in (lb/inch)/(lb/1000 ft^2).]

Based on the foregoing discussion and visual evidence, compressive strength is highly dependent on fiber bonding (density) and is believed to be limited by the fiber modulus or strength on well-bonded sheets. In the normal papermaking ranges we believe that density plays a major role in determining compressive strength as well as other properties. Practical ways to increase density or bonding are needed.

DENSIFICATION

Wahlstrom (18) in a recent review concluded that the major breakthroughs in water removal will be achieved by using extended nips to increase time at the nip and press impulse ten-fold, and by using steam boxes to raise temperatures to the 70-80°C range. Higher temperatures reduce viscosity, soften the fibers and reduce rewetting. He concluded that these and other changes such as higher nip pressure, felt selection and double-felting may produce dryness improvements of 5-10%. To achieve the high temperatures economically, he recommended condensing steam in the sheet before the last nip.

In recent work Andersson and Back (19) used the dynamic press simulator developed by Wahren and Zotterman (20) to confirm that up to 8% higher dryness may be achieved in pressing by heating the wet web to 90°C. Several furnishes, including unbleached kraft at various degrees of refining and basis weight, were studied. Third press conditions in terms of pressure and speed were simulated. For these conditions the sheet solids contents increased from 38% into the press to 40-50% out of the press at 90°C depending on basis weight and refining (see Fig. 13 and 14). At 30°C the solids content increased from 38 to only 39-42%. Thus, increases of up to 8% additional solids content were achieved at the elevated temperature. These results confirm the projections made by Wahlstrom (18). This new development could be significant based on energy alone, but will have even greater potentials because the higher densities achieved should increase compressive strength and other sheet properties.

For highly delignified pulp the improvements in dryness are caused by water viscosity effects. For lignin-rich pulps the thermal effect is greater than expected based on water viscosity changes. Andersson and Back (20) indicate the greater effects may be due to thermal softening of the lignin or reduced rewetting of the pressed web. Thus, it appears the process may have added advantages when high-yield fibers are used in linerboard. They indicate that development work will be required to obtain the advantages of the heated press approach.

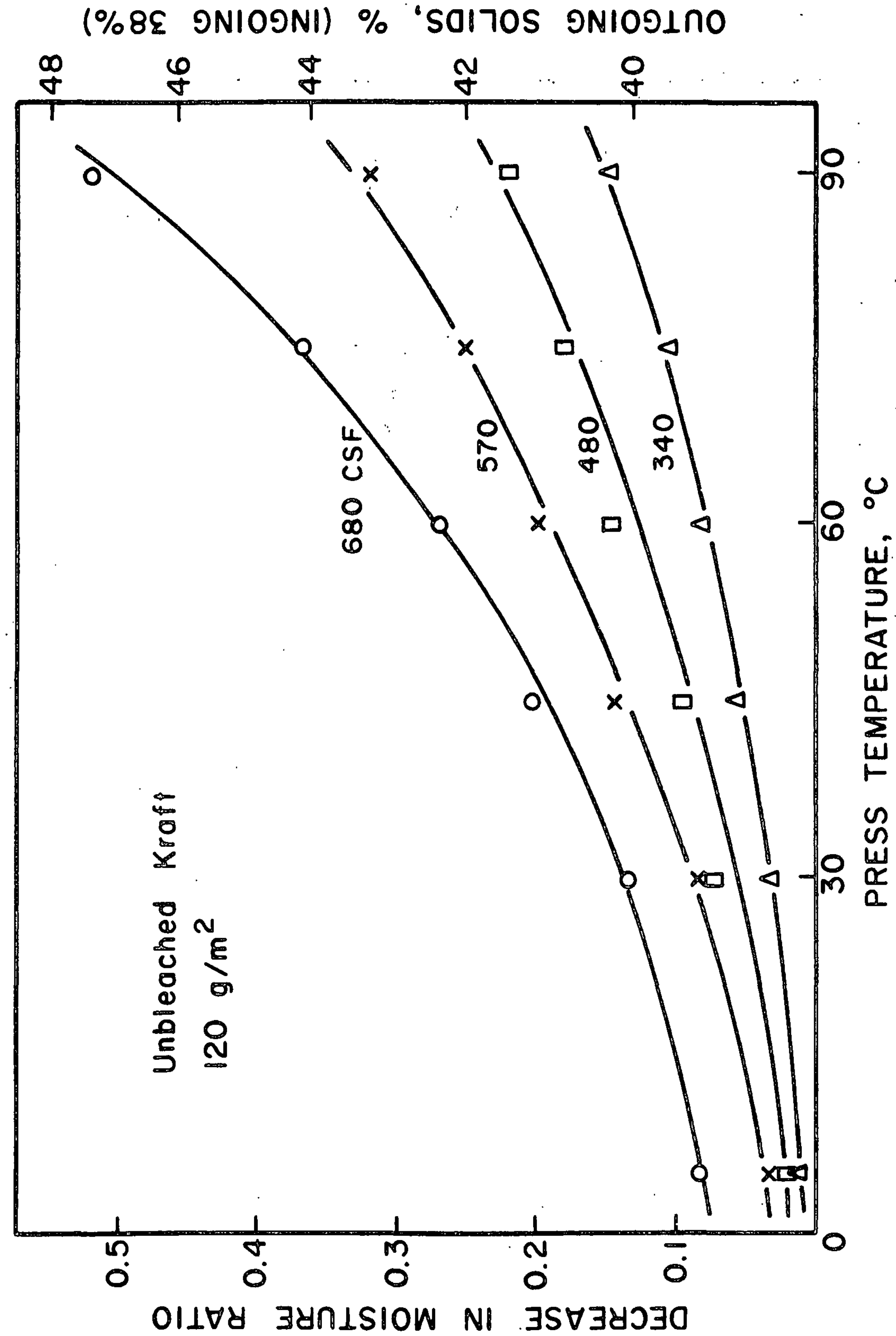


Figure 13. Effect of pressing temperature on removed wet moisture ratio and outgoing solids for unbleached kraft [Andersson and Back (19)].

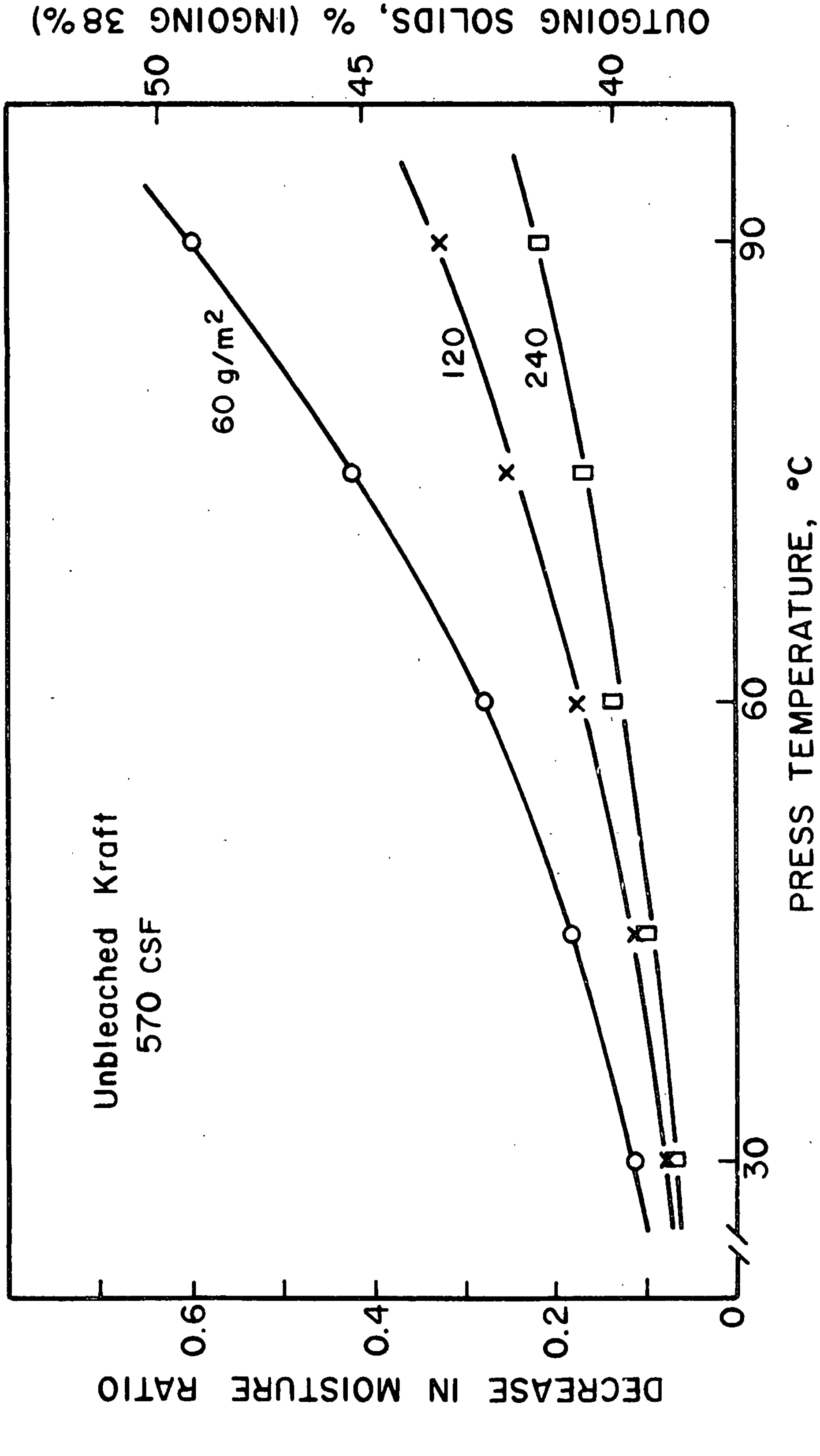


Figure 14. Effect of pressing temperature on water removal for unbleached kraft at various basis weights [Andersson and Back (19)].

A recent survey of high PLI double felted presses by Perrault (21) indicates that bursting strength and/or speed is generally improved with better pressing. Most often, less refining is employed to stay within specifications and to obtain a dryer sheet out of the press. In some cases a rougher top surface is obtained. Unfortunately, no information on compressive strength or the many other board properties was included.

In discussing the extended nip press, Justus and Cronin (22) indicate that, other things being equal, dryness increases with freeness, sheet temperature, time in the nip and average nip pressure. They indicate that, generally, burst, ring crush, tensile and density are increased by 10-20% as the sheet dryness out of the press increases (Fig. 15). They also indicate that reductions in drying energy may be about 20-25% or more.

We believe that the density changes associated with improved pressing should improve both costs and most board properties, including compressive strength.

The press-drying research at the Forest Products Laboratory by Setterholm (23-25), Horn (26), and Von Byrd (27) has shown that high-yield hardwoods can be used to give sheets with high edgewise compressive strength (Fig. 16). The high pressures and temperatures during press drying result in high densities and fiber-to-fiber bonding.

Press drying improves most properties of the sheet that are dependent on fiber bonding but results in somewhat lower tearing strength.

For example Setterholm (23) indicates that "with the exception of tearing resistance, high yield sweet gum handsheets performed as well or better than press-dried handsheets from high-yield Douglas-fir;....". In general the restraint and

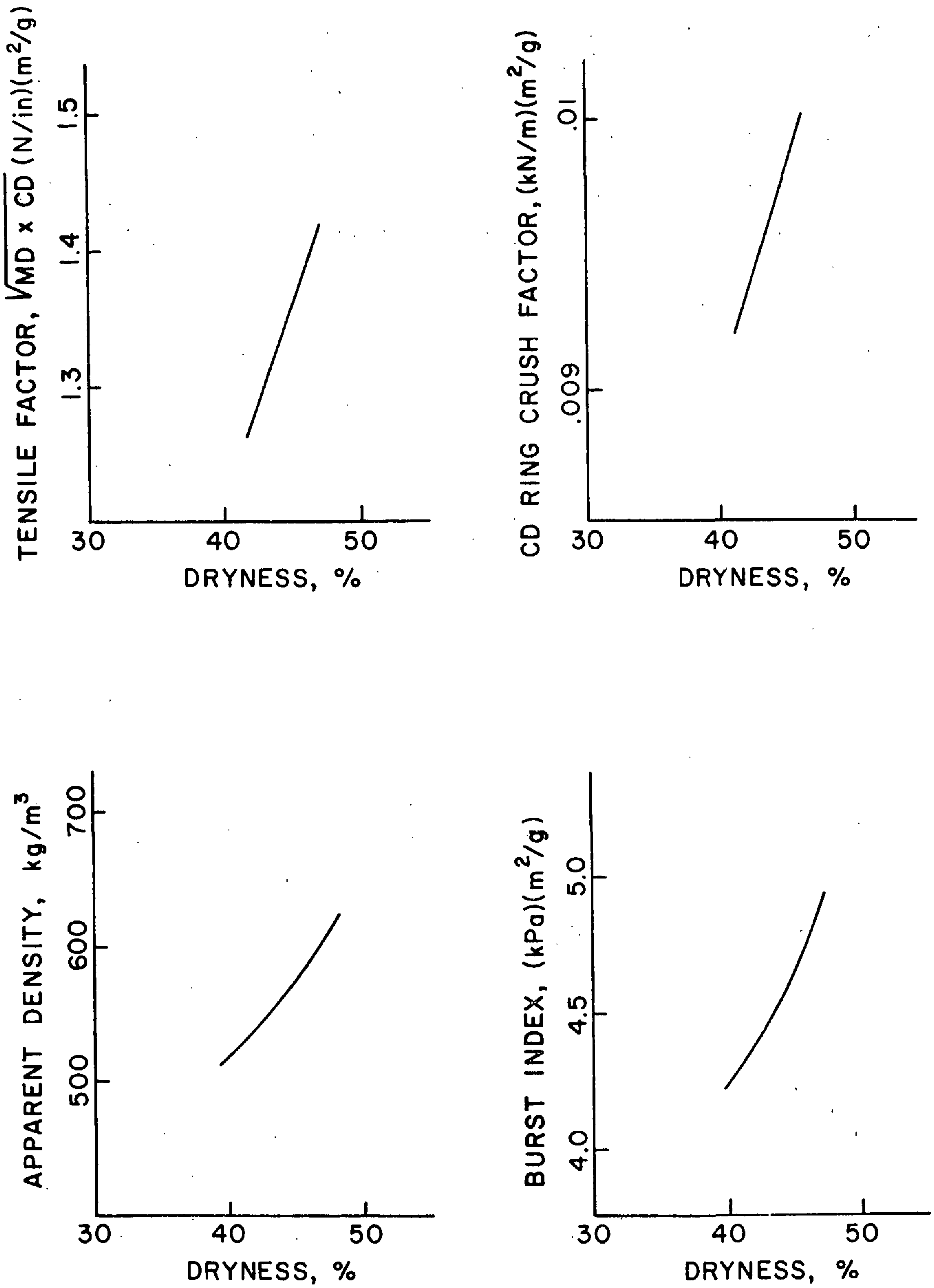


Figure 15. Sheet properties vs. different drynesses out of the press [Justus and Cronin (22)].

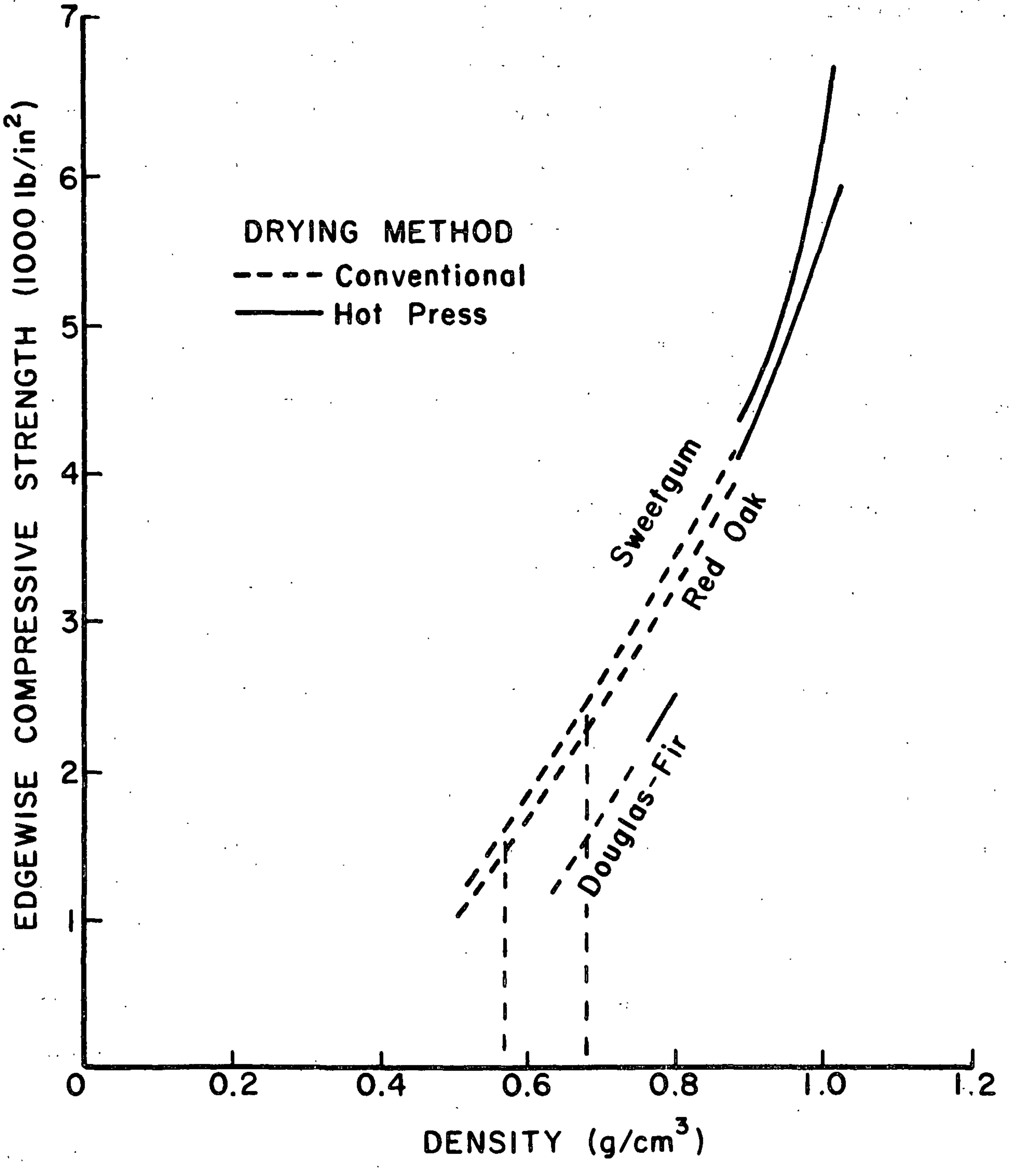


Figure 16. "Press drying increases edgewise compressive strength for handsheets for three pulps; hardwoods produce a stronger sheet than does softwood Douglas-fir." [Setterholm and Benson (23)]. [Density range for commercial 42-lb kraft liner shown by dashed vertical lines.]

densification obtained using press drying increases compressive strength, tensile strength and Young's modulus. On beaten pulps the densification obtained with press drying gave bursting strengths about the same as obtained with refining and conventional drying. However, bursting strength increases were obtained on unbeaten pulps. Concerning tearing strength, press drying tended to reduce the maximum attainable tear.

These results emphasize the strong effects of density on most board properties. The high densities promote fiber-to-fiber bonding and improved strength. By this approach stiff hardwood fibers can be utilized to obtain relatively high compressive strengths and other properties.

The high levels of bonding are believed to be due primarily to the flow of the hemicelluloses under heat and pressure. However, recent work at the Institute shows that cold (room temperature) press-dried hardwood sheets exhibit compressive and tensile strengths in the same range as hot press-dried sheets at equivalent densities (Fig. 17 and 18). In Fig. 17 compressive strength data on "cold" press-dried handsheets made from loblolly pine and gum pulps are plotted vs. density. For comparison purposes FPL data on handsheets given (1) hot press drying or (2) "cold" press drying at high moisture followed by oven drying on rings are shown. While there are differences in fiber species and refining, the unrefined cold press-dried IPC sheets attain at least equivalent compressive strengths at equal densities. The lignin and hemicelluloses apparently can flow and produce high fiber bonding even at room temperature; i.e., high temperatures are not necessarily required. The tensile results in Fig. 18 show similar trends. Long drying times are involved at room temperature, but the results raise basic questions on the development of fiber bonding.

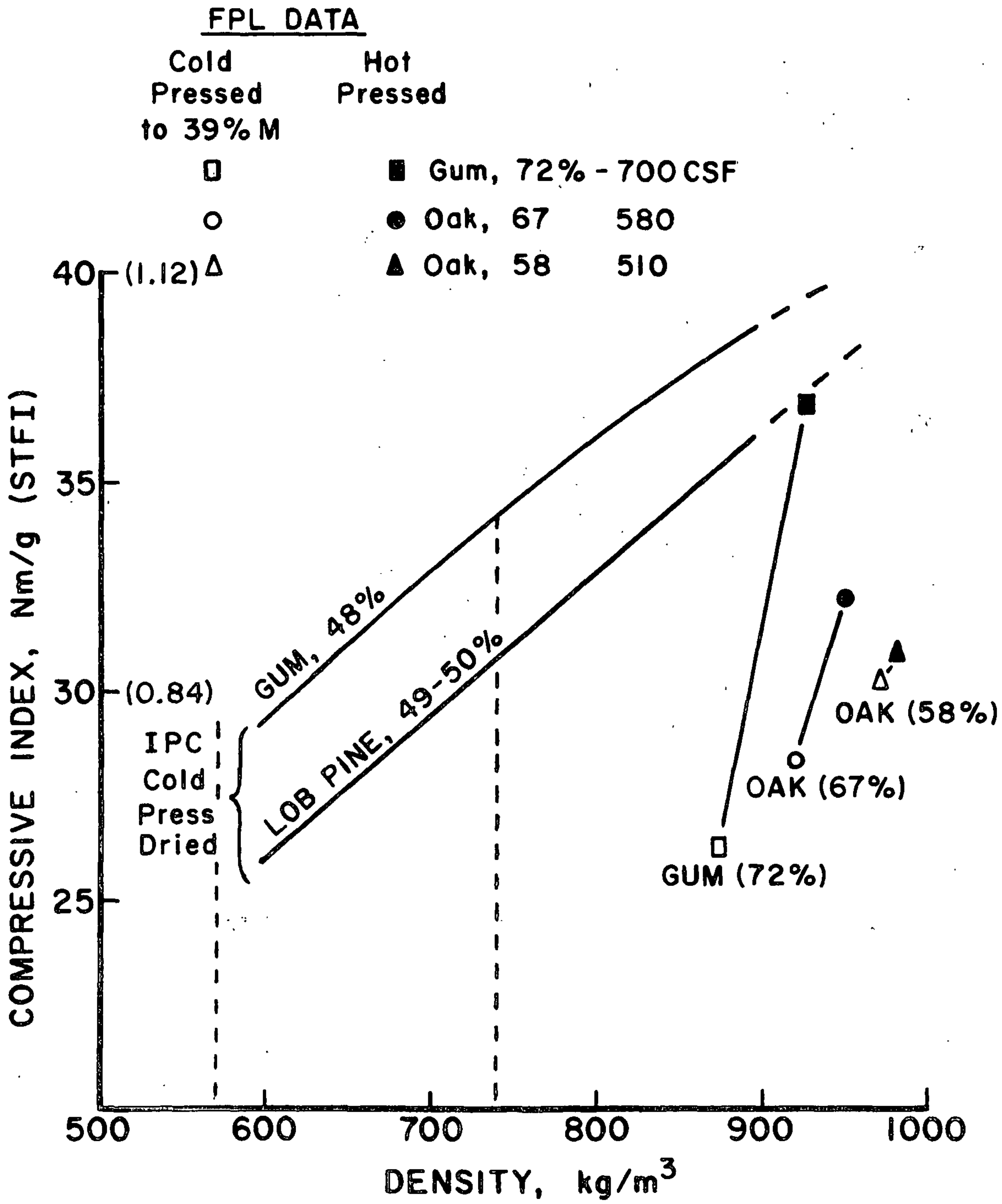


Figure 17. Compressive strength comparisons for various press-drying techniques. [FPL data from Ref. (23); IPC data from Ref. (4)]. [Density range for commercial 42-lb liner shown by dashed vertical lines; load scale values in parentheses are in (lb/inch)/(lb/1000 ft^2)].

Ince (28) projects significant savings by press drying high-yield hardwood furnishes. As an example, savings in wood costs of $25-32 per metric ton were estimated.

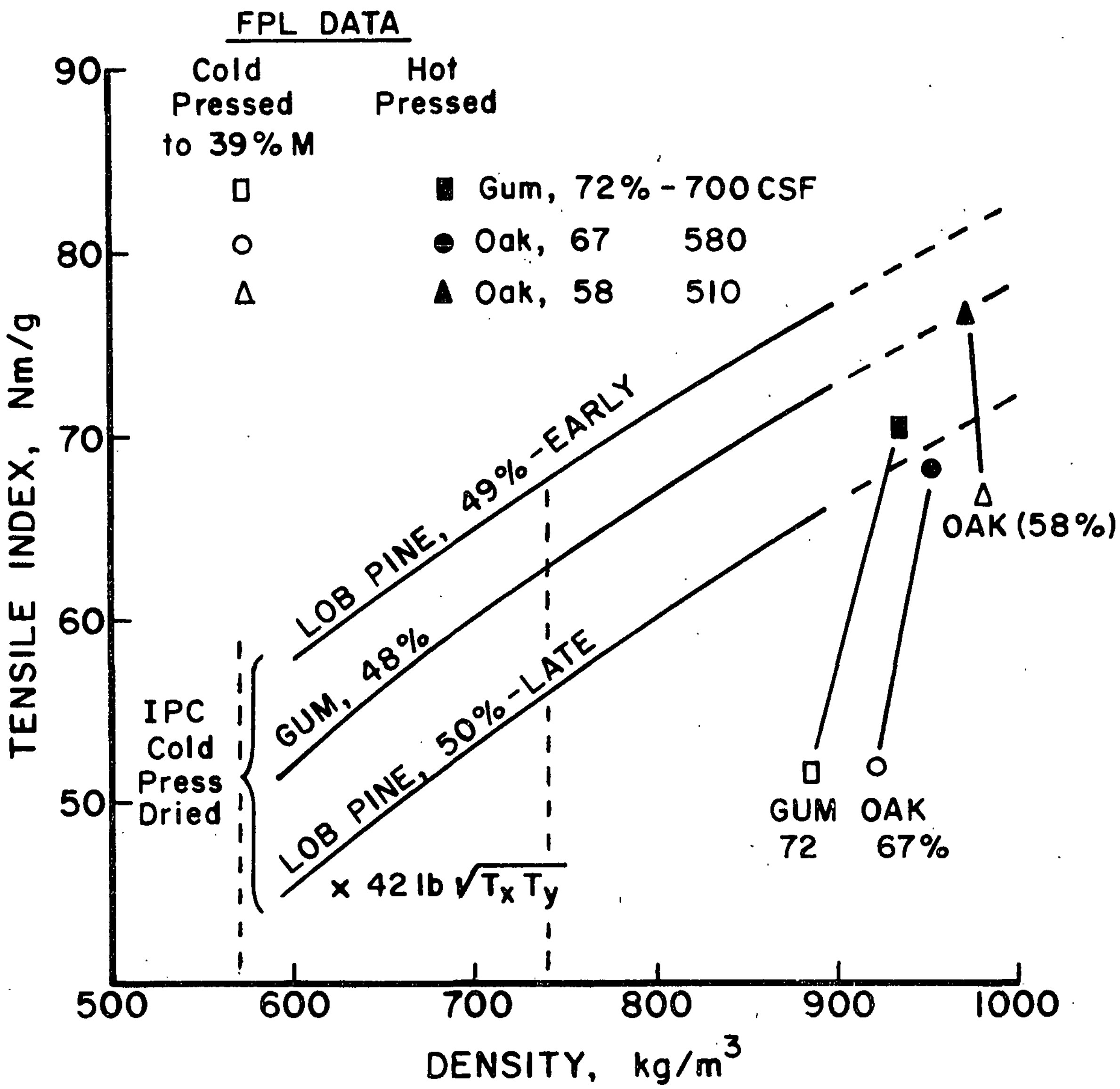


Figure 18. Tensile strength comparisons for various press-drying techniques. [FPL data from Ref. (23); IPC data from Ref. (4)]. [Density range for commercial 42-lb liner shown by dashed vertical lines.]

We believe these results indicate that greater use can be made of hardwoods and recycled fiber in linerboard. Both furnishes have good compressive strength potentials if properly utilized.

FIBER FURNISH AND YIELD

Various fiber furnishes differ in their compressive and tensile potentials at a given density. For example, Fig. 11 and 12 taken from work by deRuvo *et al.*

(13) show that NSSC hardwoods and recycled corrugated (OCC) have relatively good compressive potentials relative to unbleached kraft. The tensile characteristics of the hardwoods and OCC were less favorable. Our work on recycled corrugated also shows that the medium fraction has high compressive strength (29).

Worster (30), who recently reviewed factors associated with the use of hardwood/softwood linerboard blends, notes that a relaxation of Rule 41 should make it possible to use more hardwood in linerboard. Worster (30) comments on a number of mill factors associated with hardwood use. In mills designed for processing only pines, these factors include more difficult barking, higher energy requirements for chipping, higher loss of wood substance in outside chip pile storage and lower heat value of hardwood bark on a weight basis. Tall oil recovery may also be lower. Japanese and Columbian work is cited to show that linerboards with high hardwood contents can be manufactured with good compressive strength but with lower Mullen (31,32).

In earlier work Worster (33) showed that pulping mixed softwood/hardwood blends overcooks the hardwood portion. Separate pulping trials were then made. Duplex linerboards made with varying percentages of green liquor hardwood pulp (70% yield) in the bottom sheet were compared (Table II). Up to 20% separately cooked hardwoods could be incorporated in the bottom sheet without any major effect on ring crush or tearing strength. These were accompanied by a loss of about 18% in Mullen. Fiber yield increases, reflecting the addition of the 70% yield hardwood.

Sproul (34) reported results obtained on blends of NSSC hardwoods and southern kraft. The trials were carried out at Herty Foundation on a 31-inch Fourdrinier. For blends of up to 30% hardwood, Table III shows that CD ring crush was constant. Burst decreased by 19% relative to the unbleached kraft control but was still at a level of 99 psi for a nominal 42-lb sheet. Relatively large decreases in tearing strength were obtained. Losses of 13 to 18% in tensile strength were obtained at 30% hardwood addition. As the hardwood content increased from 0 to 30%, the density decreased from 610 to 530 kg/m^3. Improved densification of the high hardwood content sheets would be expected to improve ring crush, tensile and burst. Sproul included that with "judicious refining, blending and balancing of papermaking conditions, up to 30% of high yield NSSC pulp can be used on linerboard."

TABLE II[a]

EFFECTS OF 5 TO 20% GREEN LIQUOR HARDWOOD PULP IN BOTTOM LINERBOARD ON DUPLEX LINERBOARD PROPERTIES - KRAFT PULP FROM PINE ONLY

Top Sheet					
Pine kraft pulp, %	100	100	100	100	100
Kappa number	72	72	72	72	72
Bottom Sheet					
Pine kraft kappa number	94	94	94	94	94
% Green liquor pulp	0	5	10	15	20
Beat. rev. to 630 ± 5 mL CF	4.2	3.8	3.5	3.2	2.8
Duplex Linerboard Properties					
Mullen	123	118	117	108	101
Ring crush	67	66	65	65	65
Tear	194	200	198	198	193
Internal bond	179	172	178	168	166
Caliper	7.4	7.6	7.6	7.9	8.1
Brightness	18.2	18.5	18.3	18.7	18.8
Total Linerboard Yield, % on b.d. wood	54.2	55.0	55.8	56.6	57.4

[a]From Worster, H. E. (33).

Shick and Snow (35) studied the sulfite-sulfide-carbonate pulping process for high-yield pulping of southern pine. Their results indicate ring crush strength was relatively insensitive to changes in yield up to about 75%. These findings are in agreement with those obtained by Seth (2) and Fellers (3), which were previously discussed. Shick concluded that the process could give a pulp superior to kraft at a given yield with respect to burst, tensile strength, ring crush and brightness. The tear results were comparable to those for kraft. Taking burst and ring crush results into consideration, Shick indicated that sulfite-sulfide-carbonate pulps at 70-75% yield could replace kraft pulps at 50-60% yield for linerboard manufacture.

TABLE III

SUMMARY OF PAPERMAKING AND LINERBOARD PROPERTIES[a]

Run No.	7161	7163	7165	7165	7166	7167
Southern kraft, %	100	90	85	80	75	70
NSSC, %	0	10	15	20	25	30
Freeness chest, C.C.	584	597	584	598	585	582
Freeness headbox, C.C.	552	559	530	526	550	505
Consistency, %	0.43	0.47	0.48	0.53	0.48	0.51
Ream wt. (24 x 36 - 500)	128	127	127	121	122	122
Caliper, mils	13.4	14.3	14.2	13.9	14.0	14.7
Apparent density, g/cc	0.61	0.59	0.57	0.57	0.56	0.53
Bulk, cc/g	1.63	1.75	1.75	1.79	1.79	1.88
Mullen, points	128	97	104	103	110	99
Mullen, %	100	76	82	85	90	81
Tear, g/sheet						
MD	355	308	302	275	286	274
CD	406	392	379	328	339	301
Stretch, %						
MD	2.5	2.4	2.5	2.5	2.7	2.7
CD	2.8	3.9	3.8	4.1	4.3	4.6
Ring crush, lb						
MD	76	59	68	66	62	75
CD	60	55	56	60	61	61
Stiffness, Sheffield						
Wire side	355	363	366	373	366	353
Felt side	382	383	391	390	387	379
Gurley porosity, sec/100 mL	6.8	5.0	7.4	6.3	5.9	5.1
Brightness, photovolt	23	23.5	23.0	22.5	22.5	22.5

[a]From Sproul, R. C. (34).

These results indicate the potentials of greater utilization of higher yield pulps in linerboard to maintain and improve strength properties and reduce costs.

Linerboards and corrugating mediums made from high amounts of Philippine and Columbian hardwoods have been studied at the U.S. Forest Products Laboratory under the foreign aid program (36,37). Koning et al. (36) made nominal 42-lb starch surface sized linerboard from 50/50 mixtures of Philippine hardwoods and western kraft softwoods on an experimental paper machine. They also made corrugating medium from 100% high-yield kraft Philippine hardwood screenings. The linerboard exhibited low bursting strengths, and it was necessary to starch size or increase the basis weight from 42 lb to 47 lb to obtain bursting strengths of 100 or more. The CD ring crush values for the hardwood mixture linerboards ranged from about 80-85 lb without starch sizing. With starch sizing CD ring crush values of 100 or more were attained. These were lower than the 100% softwood control which had a CD ring result of 112 lb. However the softwood control was refined to 500 cc CF, and hence, its ring crush strength may have been somewhat high. For example, in Project 2694-13 the CD ring compressive strength averaged over 44 commercial sample lots was about 88 lb on 42 lb commercial linerboards (38). Also, in Project 2697-3 42-lb kraft liner samples (0-30% recycled fiber) had an average CD ring strength of about 77 lb (39). Thus, the CD ring crush values obtained with the experimental hardwood mixture were about in the range obtained with domestic 42-lb linerboards.

The experimental linerboards exhibited tearing strengths and Young's moduli comparable to those of the control. Combined boards made with the experimental linerboards gave low bursting strengths as would be expected and showed more tendency to crack when scored.

The box compression tests on very small boxes made with the experimental hardwood mixture linerboards were about the same as the control in end and side load tests. However the top load results on the experimental hardwood boxes were about 9% lower than the control. This apparently reflects the differences in ring crush strength between control and hardwood boards discussed above.

Bormett et al. (37) carried out a similar study using 50/50 mixtures of high-yield Columbian hardwoods and western kraft softwood. Without starch surface treatment the linerboards had low burst. Starch surface treatment increased burst by as much as 30%, but the burst values were only about 90 psig (42 lb basis weight). The CD ring crush values on the 50/50 hardwood boards ranged from about 4 to 34% lower than the control depending on yield and starch treatment. However, the control exhibited a relatively high CD ring strength as discussed previously. Even with starch treatment of the hardwood mixture liners, the combined boards exhibited low bursting strengths and short column strengths. The compressive results on the small boxes made with the hardwood mixture liners were considerably lower than the control boxes made with softwood kraft. The box compressive strength results obtained with high Columbian hardwood mixtures were not as high as those obtained with the Philippine hardwood mixtures tested by Koning.

Summing up the work by Worster and Sproul indicates that hardwood additions of 20% or somewhat more could be used in linerboard if lower burst levels could be tolerated. These are within the range of current technologies, but optimization of pulping, refining and pressing is needed. The FPL work on press drying indicates that very high hardwood contents up to 100% will yield sheets with most properties comparable to low-yield softwoods if pressed and dried to high densities. While tearing strength is not improved by press drying, it is also not subject to the losses that normally occur due to refining. However, practical technology for obtaining the full benefits of press drying are still needed. In the intermediate ranges of hardwood usage, the FPL work with tropical hardwoods suggests that improved technologies (pulping, refining, forming, and pressing) are necessary to make better use of the hardwood/softwood fiber potentials. The relative insensitivity of compressive strength to higher yields provides further incentive for work on hardwood utilization.

FORMING

Compressive strength increases rapidly as the z-direction bonding strength increases up to a certain level of bonding (15). Above this level of bonding compressive strength increases slowly as z-direction tensile increases. As mentioned earlier, high consistency forming produces large increases in internal bonding. These are accompanied by increases in compressive strength. Table IV, taken from Grundstrom et al. (16), compares the properties of pilot scale conventional and high consistency formed (3-6% consistency) medium. The greater z-direction fiber orientation of the high consistency formed medium resulted in increases of about 20% in Concora (CMT) and compressive strength and a large increase in Scott bond. However, the burst and tensile strengths of the high consistency formed medium were about 33% lower. The MD tensile strength for the high consistency formed sheets was low because it may be more difficult to obtain a preferential MD fiber alignment in high consistency forming. Low MD tensile strengths could adversely affect the fluting performance of corrugating medium and cause some linerboard problems, e.g., scoreability.

High consistency forming apparently offers another avenue for compressive strength improvement. However, the tensile losses may be excessive. This would be particularly true in the case of medium because low MD tensile strength could promote flute fracture if not compensated for by other means, e.g., a low friction surface. Grundstrom does observe that the high consistency sheets dewatered readily due to the small amount of water to be removed and the open sheet structure. Also, at the same density the high consistency sheet was about 2% drier after the press section. An engineering assessment of the merits of this approach should be carried out.

TABLE IV

PILOT SCALE CONVENTIONAL _VS._ HIGH CONSISTENCY CORRUGATING MEDIUM[a]

Property	Conventional	High Consistency	Difference, %
Basis weight, g/m^2	152	151	-0.7
Density, kg/m^3	550	560	+1.8
Tensile index, knm/kg			
MD	60	33	-45.0
CD	30	26	-13.3
$(MDXCD)^{1/2}$	43	29	-32.6
Burst index, nm/kg	1.8	1.2	-33.3
Tear index, nm^2/kg	6.0	6.5	+8.3
CMT 30, N	230	280	+21.7
Bending stiffness, mNm	3.0	3.0	0.0
Compressive strength, MPa	15	18	+20.0
Scott bond, J/m^2	200	420	+110.0

[a]From Grundstrom, _et al._ (_16_).

In principle, use of multilayer sheets is another approach to improving fiber economy or improving strength properties. Combination boxboards have traditionally been multilayer structures usually comprised of a number of different furnishes. By furnish selection or differential refining, sheets with bulky center layers and "stiff" outer layers can be made which have good bending stiffness. Sheets of this type may also have advantages in corrugating or other forming operations where a low transverse sheer modulus in the direction of forming is important.

Another potential advantage of multi-ply sheets is that the sheet structures can be optimized with regard to strength and surface properties by furnish selection, lower cost fibers such as hardwoods or recycled fibers, differential refining, surface sizing, fiber orientation and drying restraint.

Bergstrom (40) recently summarized experiences with the Beloit Stratafló Converflo type headbox installed on the linerboard machine at Obbala. This makes a 3-ply sheet. Virgin unbleached kraft is used in the outside plies and mixtures of recycled fiber and virgin pulp in the center ply. The burst and CD ring results meet test requirements for standard Scandinavian linerboard. He cites results to show that a 3-ply sheet with 25% waste in the center ply gives burst results comparable to a 100% kraft sheet. On the other hand, mixing the components in a single layer sheet gave about 10% lower burst. The stratified sheet with 25% waste had slightly higher ring crush and bulk and 25% higher bending stiffness.

In another linerboard trial Bergstrom added 30% hardwood kraft to the middle ply and refined the softwood kraft in the outer layers more to maintain burst. Under these conditions a 10% increase in ring crush was obtained with a lower furnish cost.

Grossman (41) has discussed applications of the Voith Duoformer K to the manufacture of multi-ply linerboard. Among other things his results indicate somewhat higher burst and ring crush were obtained with 3-ply boards made from recycled OCC as compared with single ply sheets.

Setterholm and Benson (23) in their work on press drying indicate that handsheets from softwood/hardwood blends gave properties which were directly dependent on the blend ratio; the properties of blends were about the same as obtained by combining laminations of hardwood and softwood pulps. It is not clear whether this would hold true in the case of anisotropic sheets made with varying fiber orientations and drying strains. For example MD/CD compressive strength ratios are much less affected by fiber orientation and drying strains than MD/CD tensile. The transverse shear properties affecting medium forming are also less sensitive to fiber orientation and drying restraint. Thus, it may be possible to improve cost/performance ratios for forming end-use by judicious use of (laminated) structures.

DeRuvo (42) discussed a graphical procedure for optimizing the tensile and bending properties for combinations of furnishes in 3-ply sheets. The optimization can also extend to cost. Basically he assumes that the density and material properties are additive combinations of the furnishes considered. While he focussed attention on bending stiffness *vs.* tensile, the same approach could be extended to other combinations of properties such as compressive strength and burst.

Multi-ply sheet structures apparently offer possibilities for improving compressive strength in relation to other properties by utilizing differences in fiber orientation and drying restraint effects on important properties, including the transverse shear properties needed for formability and end-use. The available literature does not seem to provide sufficient information for linerboard and medium manufacture to allow a good assessment.

COMBINED BOARD ECT/DENSITY CONSIDERATIONS

Our survey indicates that increased density will increase the compressive strength and many other properties of linerboard and medium. However, there was concern that increased densification of lighter weight component grades might not increase the edgewise compressive strength of corrugated boards made therefrom because some lightweight structures fail by buckling rather than in compression. Therefore an approximate analysis was carried out to determine if increased densification of the components would increase combined board ECT even for those situations where failure is by buckling. This analysis, briefly summarized in the following text, confirms that densification is beneficial for the lightweight structures as well.

Over the years much work has been directed to establishing relationships between combined board ECT and the properties of the liner and medium. It is well known that combined board ECT is primarily dependent on the edgewise compression strengths of the linerboard and medium. One of our early studies showed that empirical prediction accuracies of about 7% can be obtained from the composite strengths of the liner using equations of the following type (43).

$$P_{my} = k_1(P_{\ell 1} + P_{\ell 2} + DP_c) + k_2 \qquad (1)$$

where P_{my} = combined board edgewise compressive strength

$P_{\ell 1}$, $P_{\ell 2}$ = edgewise compressive strength of liners

P_c = edgewise compressive strength of medium

D = draw factor

and k_1, k_2 = empirical constants

From this viewpoint papermaking factors such as densification which increase the compressive strength of the liners and medium will increase combined board ECT.

However, corrugated board is a structure. We know it is comprised of narrow plates of liner between flute tips and a series of curved plates of medium (Fig. 19). These plate elements may become unstable and buckle in the same way that a box panel buckles in top load box compression. This is more likely to take place in the lighter weight grades. When buckling occurs, the combined board ECT should be dependent on both the edgewise compressive and flexural characteristics of the liner and medium. Density has different effects on compressive and flexural properties (44). Therefore, we have been concerned that papermaking factors which increase density and compressive strength might not increase ECT in the expected way for lighter weight combined board grades. To obtain an approximate answer to this concern we carried out an analysis of the possible effects of buckling on ECT.

Recent efforts to analyze combined board ECT in terms of the plate strength of the component elements have been made by Koning (45) and Johnson *et al.* (46). A plate strength analysis was also made in Ref. (43). Koning and Johnson treat the problem as a case of inelastic buckling and assume the components are isotropic. The solutions are nonlinear and require empirically fitted CD stress-strain curves. In their present state of development it is difficult to estimate the effects of density changes on ECT strength without extensive experimentation and analysis time. Our work in Ref. (43) treats the problem in the same way as the Institute top load box compression formula - i.e., the maximum strength of the plate elements is dependent on edgewise compressive strength and the elastic buckling characteristics of the orthotropic plate elements. In Ref. (43) good prediction accuracies were obtained with an equation based on this approach. The average predictive accuracies were about 5% over a broad range of combined board constructions. We believe this approach is adequate to estimate density effects in the normal papermaking range.

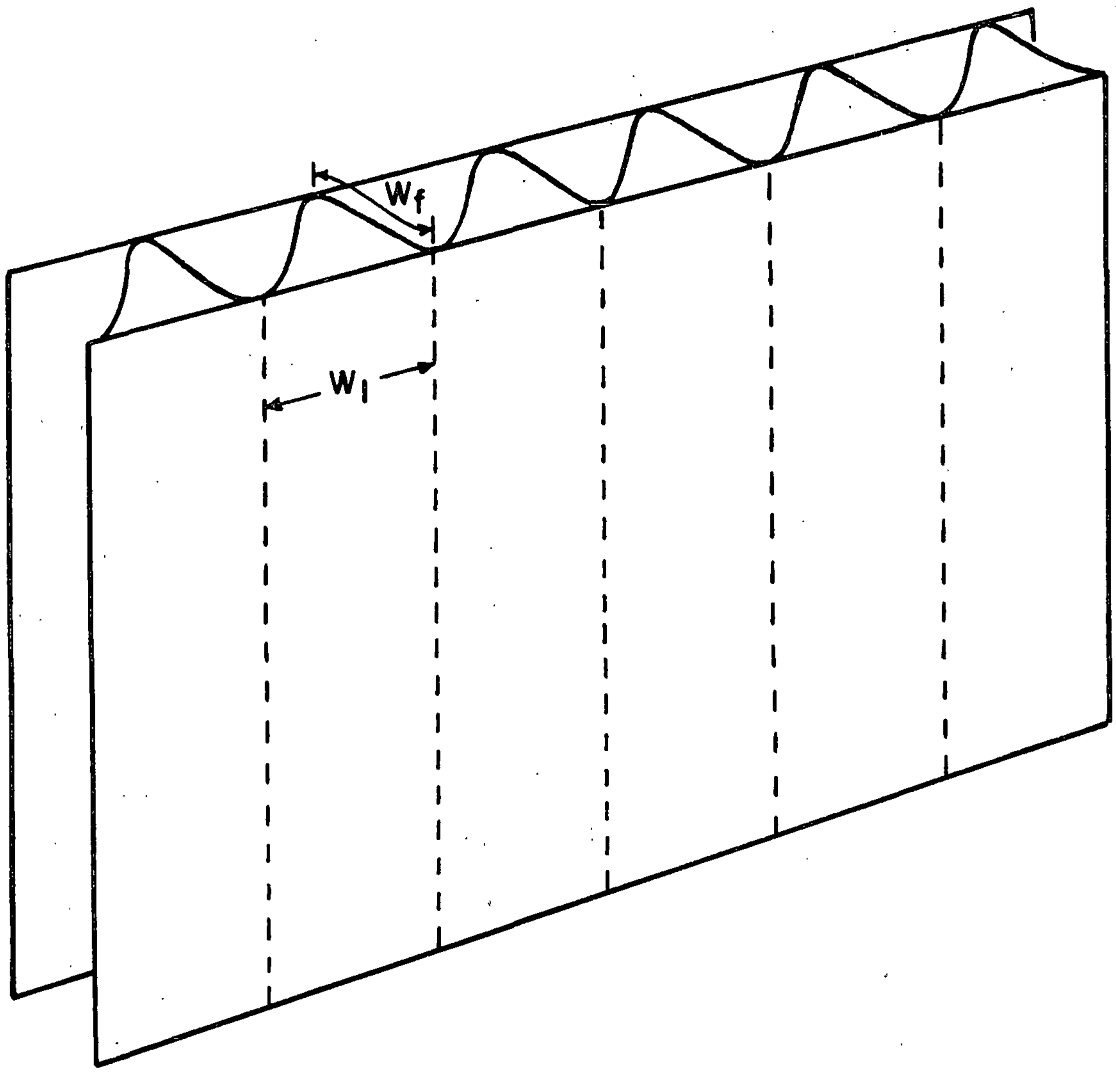


Figure 19. Corrugated board showing miniature liner and medium plate elements.

Following this approach the liner and medium contributions to ECT are formulated as follows:

$$\text{Liners} \quad P_\ell = a\, P_{r\ell}{}^{b} \left(\sqrt{D_{x\ell} D_{y\ell}}\right)^{1-b} W_\ell{}^{2b-1} \tag{2}$$

$$\text{Medium:} \quad P_c = c\, P_{rc}{}^{b} \left(\sqrt{D_{xc} D_{yc}}\right)^{1-b} W_f{}^{2b-1} \tag{3}$$

where P_ℓ, P_c = ultimate miniature plate strengths of the liner and medium, respectively

$P_{r\ell}$, P_{rc} = edgewise compressive strengths of the liner and medium, respectively

$D_{x\ell}$, $D_{y\ell}$ = flexural stiffnesses of the liners in the MD and CD directions

D_{xc}, D_{yc} = flexural stiffnesses of the medium in the MD and CD directions, respectively

W = plate width

a, b, and c = constants

The exponent b was found to be equal to 0.75. This value is the same as used in the Institute box equation. Apparently, the exponent b does not vary widely. However the multiplying constants reflect the converting technology of the time. New estimates of the constants on currently manufactured board would be desirable.

Equations 2 and 3 are combined in the same way as Eq. (1) to obtain the total combined board ECT strength.

The next question involves the effects of density on the material properties. Wahren notes that density is dependent on many factors such as refining, wet pressing and drying as well as fiber type and characteristics (44). He further notes that the influence of a given pulp on density is a specific characteristic of that pulp. For a given pulp the following general relationships can be used.

$$D = EI = k_3B^3/\rho^{3-r} \tag{4}$$

$$P_{r\ell} \text{ or } P_{rc} = k_4\, \rho^{n-1}B \tag{5}$$

where D = flexural stiffness

$P_{r\ell}$, P_{rc} = edgewise compressive strength

B = basis weight

ρ = density

and r, n, k_3 and k_4 are constants

The constants r and n vary somewhat from pulp to pulp but are usually in the range of 1.5 to 2.5 (44,47). Their magnitude is often near 2 (44).

Using these relationships in Eq. (2) or (3) it can be shown that at constant basis weight the following results:

$$P_{\ell} = K\rho^{2b-1}W_{\ell}^{2b-1} \tag{6}$$

$$\text{or } P_{\ell} = K\rho^{0.5}W_{\ell}^{0.5} \quad \text{(for } b = 0.75) \tag{7}$$

where P_{ℓ} = ultimate miniature plate strength of the liner

A similar equation would be obtained for the medium contribution.

This approximate analysis indicates that increasing density will increase combined board ECT strength even when allowance is made for buckling of the component elements. Figure 20 compares the estimated liner (or medium) contribution with a corresponding result based on the liner (or medium) term in Eq. (1). Increasing density increases the component contribution in both cases, but the effect would be less if buckling is a factor.

A similar situation prevails in the case of the medium contribution. The above analysis accounts for both material properties and flute geometry in an approximate way. It provides an initial confirmation that papermaking factors which increase bonding and hence density will increase combined board ECT strength, even when the components buckle.

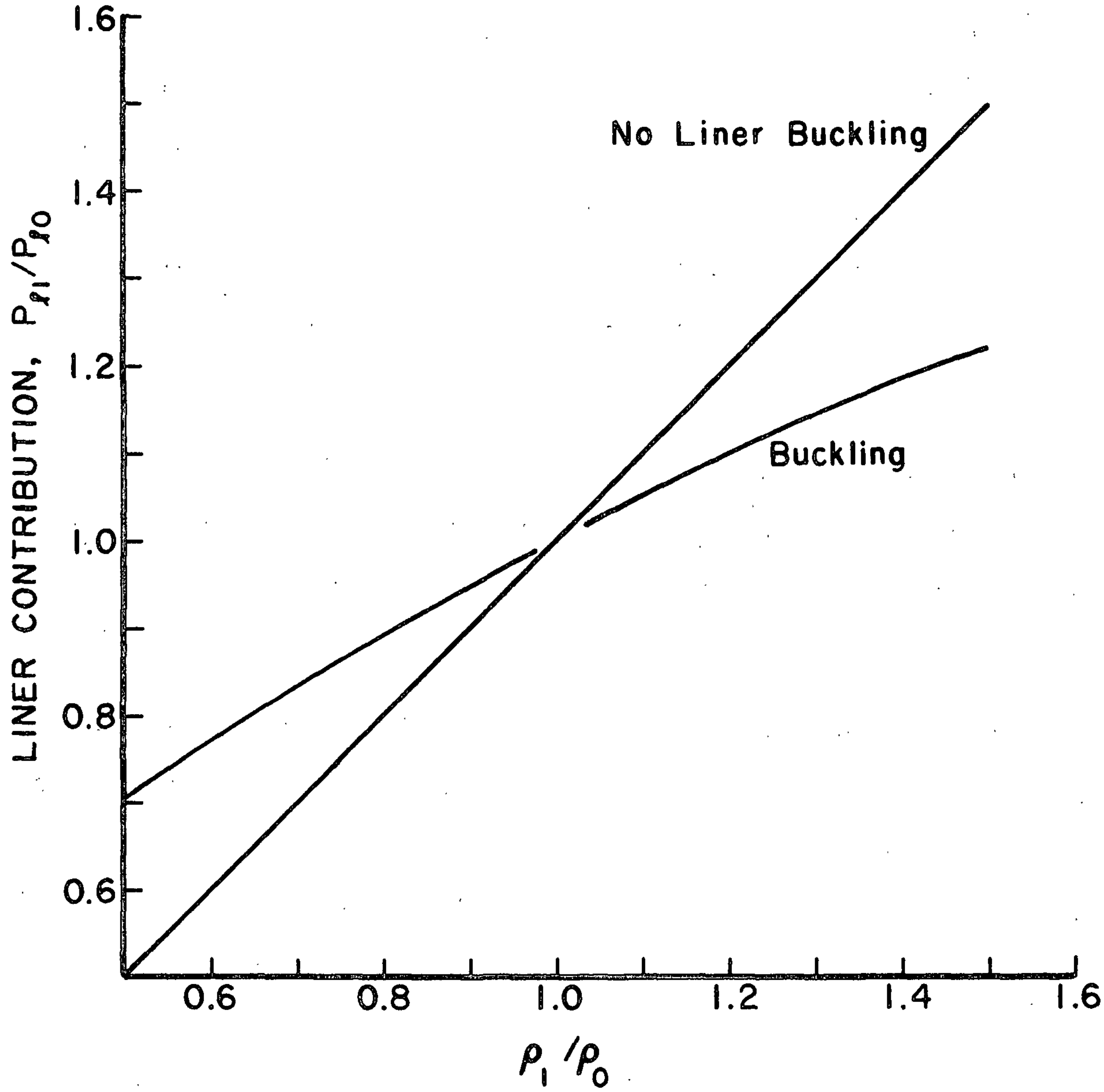


Figure 20. Estimated effects of density on the liner (or medium) contribution to combined board ECT strength (subscripts 1 or 0 denote the strength and density at a condition 1 relative to a reference condition 0).

CORRUGATING MEDIUM - DENSITY EFFECTS

The combined board flat crush load-deflection characteristics are important to performance in both the box plant and in the field. Crushed board will cause large reductions in box compressive performance. We recently reviewed the effects of crushing in relation to flat crush characteristics (48). Apparently, the initial portion of the flat crush load deflection curve is critical in determining whether crushing in finishing will degrade board quality. However, the entire load curve is important because field performance depends in part on crush resistance up to ultimate failure.

There is little information on the relation of the initial load deflection characteristics to medium properties. Future work is needed to establish this relationship. Therefore, in considering density effects we have focussed on ultimate flat crush strength.

Flat crush is dependent on the machine-direction properties of the medium. Combined board ECT will depend primarily on the cross-direction compressive properties of the medium. Thus, fiber orientation and drying restraints affect the balance between flat crush and CD compressive strength of the medium. We need to develop information to allow proper design of the sheet structure to balance MD and CD properties for formability and end-use. In the following we have assumed that orientation effects are held constant.

Brecht and Bachmayer (49) carried out an extensive study of Concora strength (CMT) which shows that papermaking factors which increase the elastic modulus raise the CMT value. In addition they indicate that CMT is dependent on thickness and point out that dry pressing can reduce CMT due to thickness reduction even though the elastic modulus appears to increase. In this case the thickness reductions bring about no real increase in fiber bonding and, hence, the actual elastic modulus of the sheet. They correlated their data using an empirical model as follows:

$$CMT = (KEt^2W)^k$$

where E = elastic modulus in direction of load

t = thickness

W = basis weight

and K, k = empirical constants

k = 0.65

Assuming that E is proportional to density squared (ρ^2), the above reduces to:

$$CMT = (KW^3)^k$$

This is an unusual result because it indicates density has no effect on CMT. However, we know most properties of paper and board are strongly dependent on density. To check their result we analyzed data on handsheets made to different weights after various degrees of refining in a study carried out for the FKBG (50).

Figure 21 shows that Brecht's relationship did not apply well. It appears to primarily reflect basis weight differences and to not explain the variations in Concora strength within a grade weight. We speculate that it overemphasizes the effects of caliper.

Figure 22 shows that the Concora results increased with increasing density at each basis weight level. The effects of density become more pronounced as basis weight increases. Figure 22 also shows that the ring compression results increased with density as expected. In Fig. 23 we show that Concora results increase with increasing compressive strength at each basis weight level.

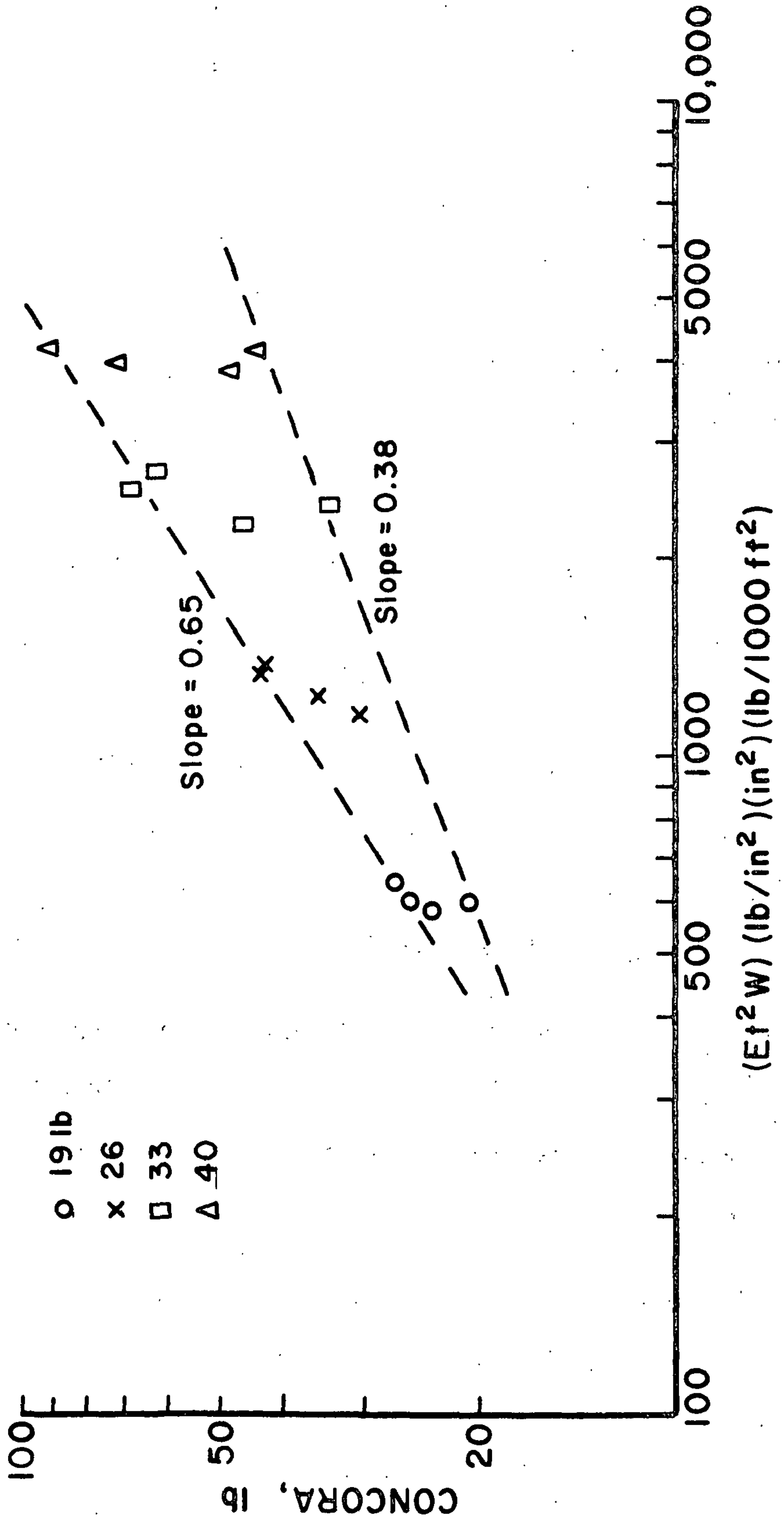


Figure 21. Test of Brecht Concora relationship (dashed lines arbitrarily drawn to envelop data).

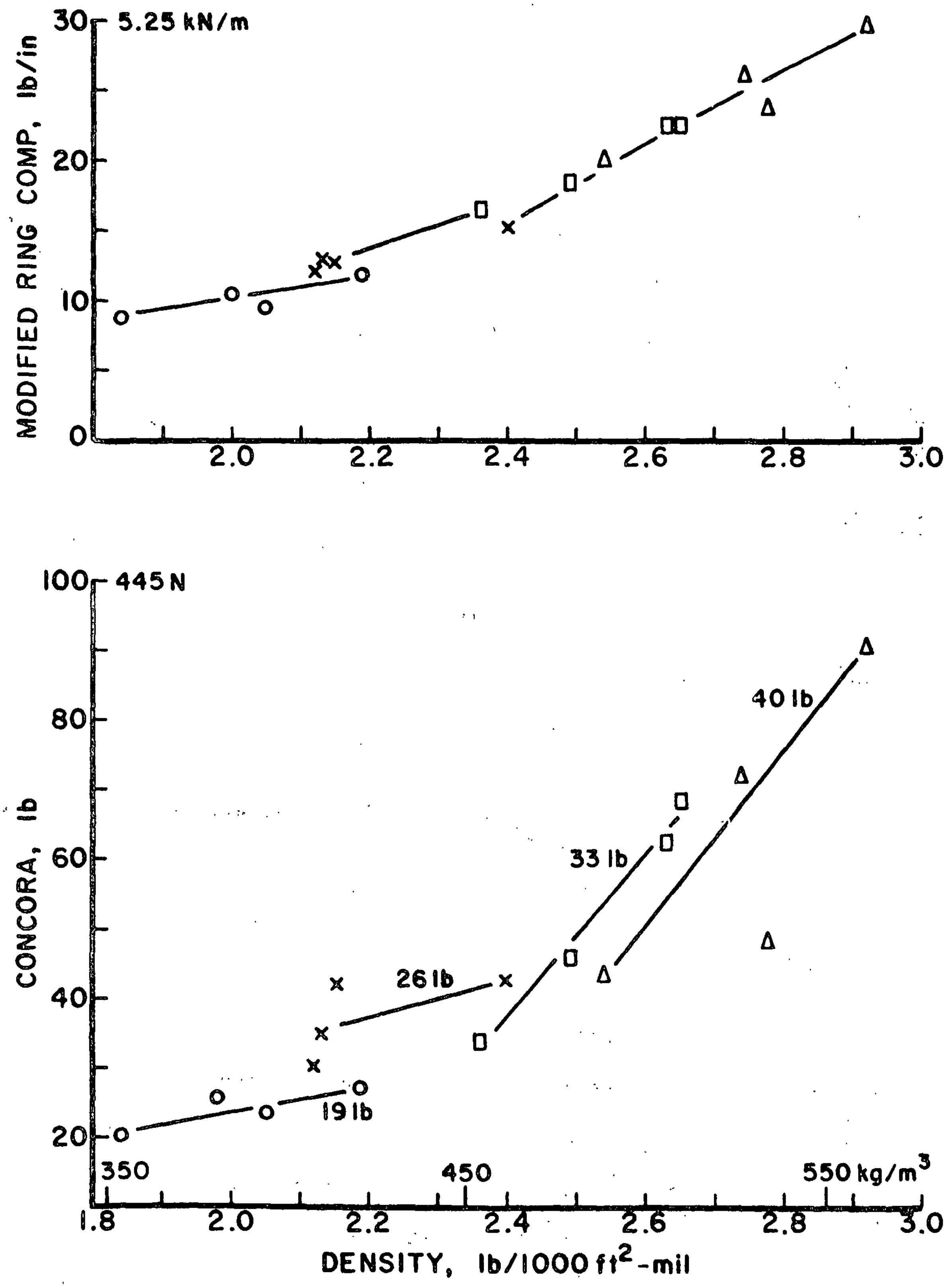


Figure 22. Effect of density on Concora and compressive strength.

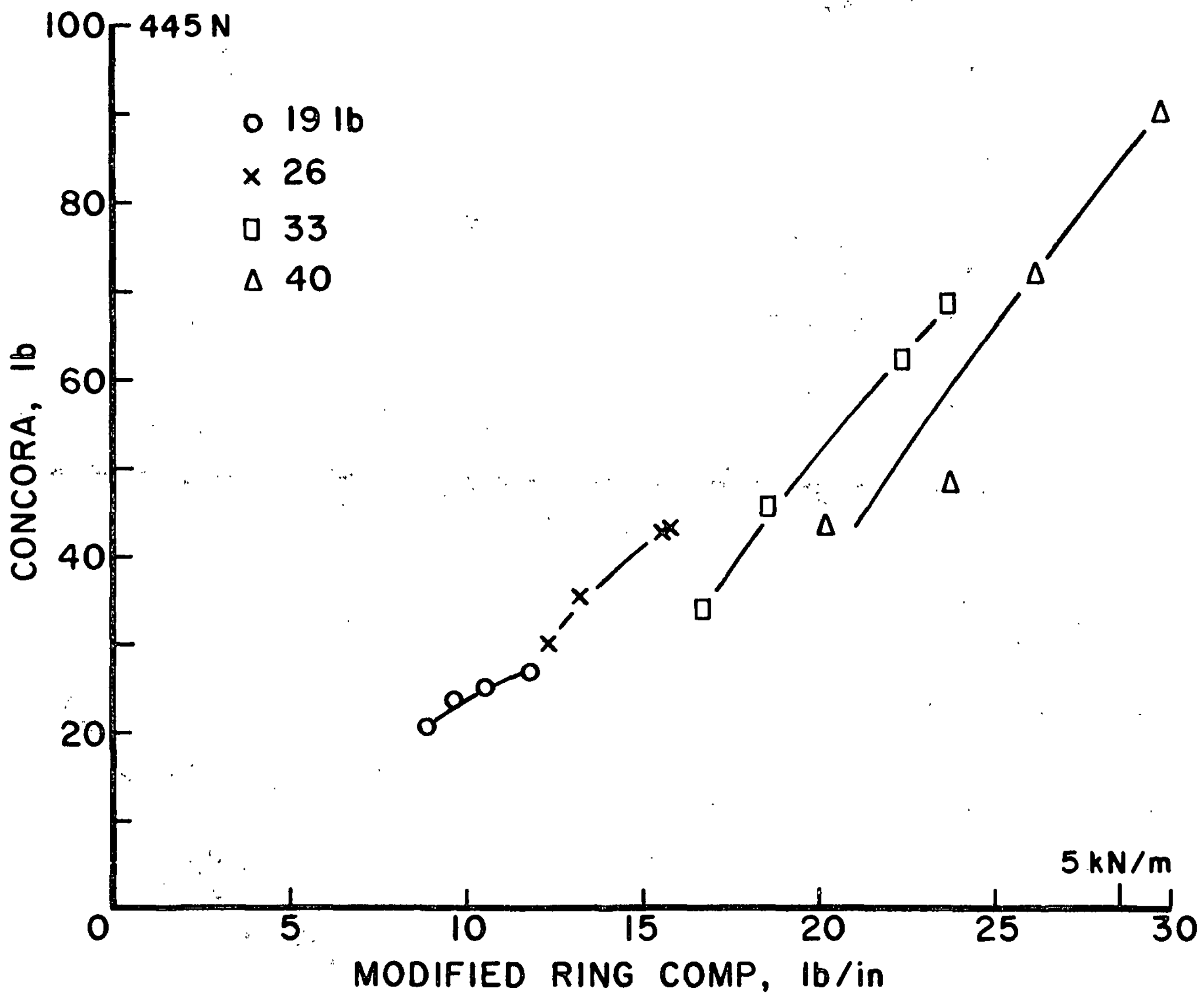


Figure 23. Relationship between Concora and compressive strength.

The results indicate that for a given furnish increasing density can be expected to generally increase both Concora and edgewise compressive strength of medium. While these two properties of medium are probably not affected in exactly the same way by papermaking furnish, process operations and by the fluting process, it appears that both increase with density (bonding). Concora depends on MD compressive strength, whereas combined board compressive strength depends on CD compressive strength. Since fiber orientation and drying strain affect MD and CD strengths differently, their effects in combination with density should be adjusted to maximize the sheet performances.

The method used to measure compressive strength may be a complicating factor in such comparisons. For example, the conventional ring test on medium usually results in a buckling failure well below the intrinsic compressive strength of the medium. Such ring results may provide misleading estimates of compressive strength because of caliper effects.

LITERATURE CITED

1. Sachs, I. B. and Kuster, T. A., Tappi 63(10):69-73(1980).

2. Seth, R. S., Soszynski, R. M., and Page, D. H., Tappi 62(12):97-9(Dec., 1979).

3. Fellers, C., deRuvo, A., Elfstrom, J., and Htun, M., Tappi 63(6):109-12(June, 1980).

4. Watt, J., Baum, G. A., and Sprague, C., Project 2695-20, Report Two to the FKBG of the API, March 15, 1981.

5. Malmberg, B., Svensk Papperstid. 65(22):911-20(1962).

6. Setterholm, V. C. and Benson, R. E., U.S. Forest Serv. Research Paper FPL L95(1977).

7. Koning, J. W. and Haskell, J. H., Pbd. Pkg. 64(10):132-50(Oct., 1979).

8. Compressive Report 84 to the FKBG Project 1108-4, Nov., 1966.

9. Compressive Report 87 to the FKBG Project 2696-5, Dec. 30, 1968.

10. Cavlin, S. and Fellers, C., Svensk Papperstid. 9:329(1975).

11. deRuvo, A., Cavlin, S., Engman, C. Fellers, C., and Lundberg, R., Papier 29(7):280(1975).

12. Koning, J. W., Jr. and Haskell, J. H., Pbd. Pkg., Oct., 1979.

13. deRuvo, A., Fellers, C., and Engman, C., Svensk Papperstid. 18:557-66(1978).

14. Whitsitt, W. J., John, B., and Sprague, C., Project 2697-3, Report Two to FKBG of API, May, 1980.

15. Whitsitt, A. J. and McKee, R. C., Project 2695-12, Report One to the FKBG, Jan. 21, 1972.

16. Grundstrom, K. J., et al., Tappi 59(3):58-61(March, 1976).

17. Perkins, R. W., Jr. and McEvoy, R. P., Tappi 64(2):99-102(Feb., 1981).

18. Wahlstrom, B., Tappi 64(2):57-60(Feb., 1981).

19. Andersson, L and Back, E. L. TAPPI, 1981 Engineering Conference Proceedings (Atlanta, GA) Book 1:311.

20. Wahren, D. and Zotterman, C., Paper Trade J. 162:37(Aug. 15, 1978).

21. Perrault, R. D., Tappi 64(9):80-5(Sept., 1981).

22. Justus, E. J. and Cronin, D. C. TAPPI, 1981 Engineering Conference Proceedings (Atlanta, GA) Book 1:333.

23. Setterholm, V. C. and Benson, R., U.S. Forest Serv. Res. Paper, FPL 295, 1977.

24. Setterholm, V. C., Benson, R. E., Wichman, J. F., and Auchter, R. J., USDA For. Serv. Res. Paper., FPL 246, 1975.

25. Setterholm, V. C., Tappi 62(3):45-6(March, 1979).

26. Horn, R. A., Tappi 62(7):77-80(July, 1979).

27. Von Byrd, L., Tappi 62(7):81-4(July, 1979).

28. Ince, P. J., Tappi 64(4):107-9(April, 1981).

29. Whitsitt, W. J., John, B., and Sprague, C., Project 2697-3, Report Two to the FKBG of API, May 19, 1980.

30. Worster, H. E., Southern Pulp Paper Mfr. (June, 1978).

31. Matsuoka, H., TAPPI Fall Corrugated Container Conf., Toronto, Nov., 1974:21-6.

32. Gomez, C. W. and Mondragon, L., Tappi 57(5):140-2(1974).

33. Worster, H. E., Southern Pulp Paper Mfr. (Feb., 1976).

34. Sproul, R. C., Forest Prod. J. 20(6):45-51(June, 1970).

35. Shick, P. E. and Snow, R. W., Tappi 54(9):1488(Sept., 1971).

36. Koning, J. W., Jr., Laundrie, J. F., and Fahey, D. J. Agency Intern Devt. (Aid) Report No. 9 March, 1977 (available from Forest Prod. Lab., Madison, WI).

37. Bormett, D., Laundrie, J. F., and Fahey, D. J. Agency Intern Devt. (AID) Report No. 14 Nov., 1977 (available from For. Prod. Lab., Madison, WI).

38. Kloth, G. R., Whitsitt, W. J., and Fox, T. S., Project 2694-13 Summary Report to the FKBG of API, July 15, 1977.

39. Whitsitt, W. J. and Fox, T. S., Project 2697-3 Report One to the FKBG of API, July 1, 1977.

40. Bergstrom, J. I., Norsk Skogind. 133-7(May, 1977).

41. Grossman, U., Southern Pulp Paper Mfr. P26-30, Feb., 1979.

42. deRuvo, A., Svensk Papperstid. 82(3):68-9(Feb. 25, 1979).

43. Relationship between the edgewise compression strength of combined board and component properties. Project 1108-4, A preliminary report to the Technical Committee of the Fourdrinier Kraft Board Institute Inc., June 18, 1963.

44. Wahren, D. Paper Technology, Part 1, Fundamentals, The Institute of Paper Chemistry, 1980.

45. Koning, J. W., Jr., Tappi 61(8):69-71(April, 1978).

46. Johnson, M. W., Urbanik, J. J., and Denniston, W. E. FPL Report 348 (1979).

47. deRuvo, A., Fellers, C., and Engman, C., Svensk Papperstid. 18;557-66(1978).

48. Whitsitt, W. J. and Sprague, C. Mechanics of Fluting. Project 3396 Report One to Members of the IPC, June 15, 1981.

49. Brecht, W. and Bachmayer, G. A., Wochbl. Papierfabr. (11/12):383-90(1968).

50. Compression Report 87 to the FKBG, Project 2696-5, Dec. 30, 1968.

THE INSTITUTE OF PAPER CHEMISTRY

W J Whitsitt

William J. Whitsitt
Research Associate
Paper Materials & Systems Division

APPROVED BY

Clyde H. Sprague

Clyde H. Sprague
Director
Paper Materials & Systems Division

APPENDIX I

DEFINITION OF TERMS AND UNITS

Compressive strength is the load at which failure occurs when edgewise compressive forces are applied to paperboard. It is often expressed as force per specified width dimension, force per unit width or as force per unit with per unit basis weight. The latter is termed compressive index following TAPPI/ISO practice. Some writers use the term specific compressive strength. By analogy with tensile breaking length a few writers express the index in kilometers by converting force to mass. Common conversion factors are given below.

lb x 4.448 = Newtons (N)

lb/inch x 0.1790 = kilogram force/centimeter (kg/cm)

lb/inch x 0.17513 = kilo-Newtons/meter (kN/m)

(lb/inch)/(lb/1000 ft^2) x 35.84 = Newton-meters/gram (Nm/g)

Newton-meters/gram x 0.1020 = kilometers (km)

Compressive index is compressive strength per unit basis weight (see compressive strength).

Tensile index is tensile strength per unit basis weight.

Fiber orientation: Unless qualified, in this report fiber orientation refers to preferential alignment of fibers in the machine direction of the sheet. Fiber orientation is one of the causes of MD/CD directionality. High fiber orientation implies fibers are aligned predominantly in the MD.

Z-direction fiber orientation refers to paperboard made with greater than "normal" alignment of fibers in the thickness direction. Forming at high consistencies is believed to produce boards with this fiber alignment characteristic.

Drying strain refers to restraints (in the sheet plane) applied during drying of the sheet or web which restrict shrinkage or stretch the sheet. This affects the MD/CD directionality of the sheet as well as other properties. In commercial board manufacture the tension on the web in the dryers restricts shrinkage in the machine direction. Cross-machine restraints also occur during drying.

Compressive test methods: It is difficult to properly measure the edgewise compressive strength of paperboard. Bowing and buckling must be avoided as well as crushing of the loaded edges. As a consequence there are many methods for evaluating edgewise compressive strength and the results obtained differ from method-to-method. Among the methods in use are ring compression, modified ring compression, STFI strip test, Concora liner test, and various lateral support methods developed by the Forest Products Laboratory, the Weyerhaeuser Co. and Pulp and Paper Research Institute of Canada. It is often difficult to convert results from one method to another because appropriate conversion factors have not been developed. Empirical relationships between STFI results and some other methods are shown below for cross-direction tests over a wide range of linerboard weights (results expressed in lb/inch or kN/m):

STFI = 1.436 x ring compression

STFI = 1.185 x modified ring compression

STFI = 1.135 x FPL lateral support

STFI = 1.416 x Weyerhaeuser lateral compression.